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EFFECTS OF PRESSURE ON BINARY ALLOYS

PARTS V-VI

By P. W. Bridgman

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(See also inside back cover)

Effects of Pressure on Binary Alloys

V

Fifteen Alloys of Metals of Moderately High Melting Point

By P. W. Bridgman

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Introduction

In the first four papers of this series[1] data have been presented for binary alloys of a number of metals with melting points not higher than a few hundred degrees. In this fifth paper data are presented for various alloys between fourteen metals with melting points ranging up to 1500° C. The material I owe to the courtesy of other workers, none of the alloys having been prepared by me. In many cases these other workers have published extensive data for a variety of non-pressure parameters of the identical alloys measured here. I have tried to give as extensive references as possible to this other work, hoping that in this way a broad base may

be laid for a significant correlation between pressure parameters and other properties. For it remains true that theory has not been very successful in explaining the behavior of metals and alloys under pressure.

The data determined in the following are the same as in preceding papers of the series. The electrical resistance at room temperature has been determined in two pieces of apparatus; in one, pressure is transmitted by a true liquid to a maximum of 30,000 kg/cm^2; in the second pressure is transmitted by a plastic solid (AgCl) to a maximum of 100,000 kg/cm^2, giving results somewhat less accurate than those with the first apparatus because of failure of pressure to be completely hydrostatic. The linear compressibility has been determined to 30,000 with the "lever piezometer".[2] This method, which is especially adapted to the less compressible metals, is applicable only over a narrower range than the apparatus used for the lower melting alloys, which reached a maximum of 40,000 kg/cm^2, but has the compensating advantage of much higher precision. All the alloys measured here crystallize in the cubic system, so that the linear compressibility determined on a single specimen can be at once converted to cubic compressibility. Plastic shearing strength was measured in a carboloy apparatus as before, the range being 80,000 or 100,000 kg/cm^2, depending on the strength of the alloy and the consequent danger of damage to the apparatus. In some cases the alloys were so strong as to preclude shearing measurements at all, since frictional freezing of the specimen to the carboloy piston demanded stresses so high as to destroy the carboloy surface. In this paper the innovation is adopted of giving the numerical data for the shearing strength in the same tables as the values for resistance and compression. The reason for doing this is that considerable verbal description is thereby avoided. There is danger in presenting the data in this way, however, that a presumption will be raised of higher accuracy than is justified. It must be remembered that the measurements of shearing strength are of quite inferior accuracy as compared with resistance or compression. The number of significant figures given is justified only by the fact that in this way the shape of the curves can be reproduced. In general the shape of the shearing curve has considerably greater constancy on repetition of an experiment than the absolute values. In particular, too much

weight must not be attached to small trends with the composition of the shearing strengths at the same pressures, such as could be found from a reading of the tabulated results across the horizontal rows of the tables.

In addition to the measurements under pressure, the following measurements were made at atmospheric pressure, as also in the other papers of the series: specific resistance at 0° C, temperature coefficient of resistance between room temperature and 0° C, measurements being made over a complete temperature cycle to avoid any error from possible permanent changes with temperature, and in a number of cases, density.

Numerical Data

In the following several dilute alloys of silicon will first be presented and after that the other alloys arranged in the conventional alphabetical order. The greater part of the discussion will be given in connection with the individual alloys, instead of reserving it for the final section.

Copper – Silicon. The phase diagram, which at high concentrations of silicon is exceedingly complicated, shows only homogeneous solid solutions to atomic concentrations beyond 15 per cent. In the following, measurements were made on eight compositions, ranging from 0.21 to 10.14 At % Si.

The material of this and the two following Fe – Si and Ni – Si series, I owe to the kindness of Dr. C. A. Domenicali, who prepared them at the Franklin Institute for his measurements of thermal e.m.f. and resistivity at atmospheric pressure over a temperature range from –200° to 450° to 850° C.[3] The copper was 99.99% pure copper from Vacuum Metals Corporation ("Cuprovac"), and the silicon was "hyperpure" material (99.95) from the DuPont Company. The alloys were prepared in approximately 150 gram lots in vycor crucibles, and were melted in a vacuum of less than 25 μ in a resistance furnace. The ingots were homogenized 15 hours in vacuum at temperatures just below the solidus line. The resistance specimens were rolled by me and annealed at a dull red in helium after rolling. The compression specimens were annealed at a dull red and subjected to a preliminary pressure seasoning to 30,000. This pressure seasoning probably was not necessary, since

TABLE I

Copper – Silicon System

	100 Cu	99.79 Cu 0.21 Si	99.56 Cu 0.44 Si	98.86 Cu 1.14 Si	98.40 Cu 1.60 Si	97.66 Cu 2.34 Si	96.40 Cu 3.60 Si	92.49 Cu 7.51 Si	89.86 Cu 10.14 Si
$\rho \times 10^6$	1.69	2.35	3.18	5.53	7.33	9.53	13.2	21.1	18.5
Temperature Coefficient	.00436	.00369	.00220	.00123	.00098	.00085	.00063	.00047	.00054
Pressure kg/cm²				Rp/Ro					
0	1.00000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
5,000	.99054	.9920	.9942	.9958	.9962	.9962	.9965	.9966	.9964
10,000	.98195	.9843	.9886	.9916	.9925	.9926	.9932	.9932	.9931
15,000	.9737	.9769	.9831	.9876	.9888	.9892	.9900	.9899	.9898
20,000	.9656	.9698	.9779	.9838	.9853	.9858	.9869	.9866	.9866
25,000	.9579	.9631	.9729	.9801	.9820	.9826	.9838	.9835	.9836
30,000	.9506	.9567	.9683	.9765	.9787	.9795	.9810	.9806	.9805
40,000	.939	.946	.961	.972	.974	.974	.975	.975	.975
50,000	.928	.938	.954	.968	.969	.969	.970	.968	.970
60,000	.919	.930	.948	.964	.965	.965	.966	.964	.965
70,000	.911	.923	.943	.961	.961	.960	.962	.959	.961
80,000	.903	.916	.938	.958	.958	.957	.958	.955	.958
90,000	.896	.911	.933	.956	.955	.953	.955	.951	.955
100,000	.890	.905	.929	.954	.952	.950	.952	.949	.952
				$-\Delta V/Vo$					
5,000	.00387	.00360	.00362	.00351	.00343	.00351	.00343	.00357	.00354
10,000	.00759	.00713	.00714	.00701	.00685	.00698	.00687	.00708	.00704
15,000	.01117	.01054	.01063	.01050	.01026	.01040	.01029	.01053	.01045
20,000	.01465	.01390	.01404	.01398	.01367	.01382	.01373	.01391	.01382
25,000	.01800	.01720	.01739	.01742	.01709	.01721	.01721	.01725	.01715
30,000	.02119	.02042	.02065	.02088	.02054	.02055	.02065	.02053	.02039
				Shearing Strength, kg/cm²					
20,000	1,600						1,630	1,200	1,420
40,000	3,420						3,120	2,100	2,580
60,000	5,090						4,300	3,140	3,700
80,000	6,410						5,480	4,230	4,790
100,000	7,510								

the resistance specimens were not seasoned and showed no permanent change of resistance after the first (and only) application of pressure. The specific resistances given in Table I were measured on specimens in wire form about 0.050 inches in diameter (as received) instead of on the rolled specimens used for the resistance measurements under pressure (except for the one composition 10.14% Si for which a long enough wire was not available). The reason was that the geometrical dimensions are favorable to higher accuracy for the wires. The values given in the table for the resistances and compressions of " 100% " Cu were not obtained on the 99.99% Cu from which the alloys were actually prepared. The resistance measurements were made on electrolytic copper of 99.999% which I obtained a number of years ago from Dr. Greninger. Values for this have been previously published – these values are here slightly revised to fit more recent measurements. The compression measurements of the table were made on 99.999 Cu supplied by Mr. William G. Johnston of the General Electric Company. The compressions obtained with this are about 5 per cent greater than compressions formerly obtained with the 99.999 Cu of Dr. Greninger. The reason for the discrepancy does not appear. The shearing strengths in the table for " 100% " Cu were measured on 99.99% Cu, but not on the same material as for the copper-silicon alloys here, but was that used by Dr. T. J. Rowland in preparing his copper alloys, and will be more fully described later.

The various measurements went smoothly without episodes – there are no discontinuities marking phase changes, or cusps. The average deviation from a smooth curve of a single one of the compression measurements was of the order of 0.4 per cent of the maximum compression. The resistance measurements were smooth to nearly the limit of the sensitivity of the readings, one part in 15,000 on the total resistance.

The negative pressure coefficient of resistance is diminished numerically by the addition of silicon up to 7.5 per cent. This is normal. On passing from 7.5 to 10.14 per cent there is a slight reversal, which is mirrored also in the specific resistance and the temperature coefficient of resistance. There are some initial irregularities in the compression; in broad outline the addition of silicon up to 1.14 per cent increases the compression, beyond which there

TABLE II

Iron – Silicon System

	100 Fe	99.61 Fe .39 Si	99.22 Fe .78 Si	98.82 Fe 1.18 Si	98.05 Fe 1.95 Si	96.13 Fe 3.87 Si	94.25 Fe 5.75 Si
$\rho \times 10^6$	11.3	12.1	14.1	16.5	21.9	35.4	46.9
Temperature Coefficient	.00585	.00437	.00365	.00330	.00236	.00152	.00099
Pressure kg/cm²				Rp/Ro			
0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
5,000	.9884	.9898	.9911	.9918	.9940	.9968	.9991
10,000	.9773	.9800	.9825	.9843	.9882	.9936	.9982
15,000	.9666	.9704	.9744	.9769	.9826	.9905	.9971
20,000	.9562	.9613	.9668	.9704	.9772	.9874	.9960
25,000	.9464	.9526	.9595	.9628	.9720	.9844	.9948
30,000	.9368	.9441	.9526	.9563	.9670	.9814	.9935
40,000	.920	.931	.941	.945	.957	.976	.991
50,000	.906	.920	.931	.935	.949	.972	.989
60,000	.893	.910	.922	.928	.941	.968	.987
70,000	.881	.902	.914	.922	.933	.964	.986
80,000	.870	.895	.906	.916	.927	.961	.984
90,000	.861	.889	.899	.911	.922	.958	.983
100,000	.852	.884	.892	.907	.917	.946	.982
				$-\Delta V/Vo$			
5,000	.00289		.00283	.00283	.00282	.00282	.00278
10,000	.00575		.00564	.00562	.00561	.00558	.00543
15,000	.00856		.00837	.00834	.00834	.00828	.00804
20,000	.01133		.01107	.01107	.01104	.01098	.01068
25,000	.01406		.01371	.01371	.01368	.01362	.01326
30,000	.01676		.01629	.01632	.01629	.01623	.01614

is a falling off, not regular in fine detail. The shearing strengths vary considerably, but in general the shearing strength diminishes with the addition of silicon, not in the expected direction.

Iron – Silicon. Measurements were made on six compositions, ranging from 0.39 to 5.75 At per cent Si. The metallurgical phase diagram shows only a homogeneous solid solution in this range, although at higher concentrations the diagram becomes exceedingly complicated. As already mentioned, I owe the alloys to Dr. C. A. Domenicali who prepared them at the Franklin Institute. They were melted in alundum crucibles in an induction furnace in a vacuum of less than 5 μ. They were then homogenized six hours at 950° C in a vacuum varying from 3 to 5 μ. They were then cold rolled and swaged to wires of approximately 0.040 inch diameter, in which form they were supplied to me. The iron from which these alloys were prepared was 99.93% pure iron from Vacuum Metals Corporation ("Ferrovac-R"), and the silicon was from DuPont, as already described. For my measurements of resistance short lengths of the wire were rolled down to approximately 0.002 inch thickness, with several annealings at red heat. During this rolling several of the specimens broke up into longitudinal filaments, indicating seams in the wire as furnished. However, in all cases homogeneous appearing strips were obtainable large enough for the resistance specimens, and there is no reason to fear any lack of homogeneity in the measured material.

Two only of the wires as received were sufficiently perfect geometrically to justify direct measurements of specific resistance; these were compositions 0.78 and 1.95 At %. The specific resistances of these compositions given in Table II should be somewhat more accurate than the others, which were measured on strips of only 0.002 inch thickness, permitting appreciable error. The compression measurements were made on 0.75 inch lengths of wire selected as free from imperfections as possible; there were nevertheless sometimes obvious surface imperfections. All compression specimens were annealed and subjected to a preliminary pressure seasoning to 30,000.

The resistance measurements on pure iron given in Table II were not made on the same material as that from which the alloys were prepared, but on material of presumptively very high purity, although no chemical analysis was available. This material I owe

to the General Electric Company. It had been prepared by five zone melting treatments from iron originally obtained from the National Research Corporation, which showed an analysis of 0.004% C and 0.004% O. Resistance measurements under pressure on this iron agreed gratifyingly well with my previously published values for pure iron.[4] The temperature coefficient between room temperature and 0° C is slightly higher for this new G. E. iron, indicating presumptively higher purity. No attempt was made to redetermine the compression of this iron. Compression is not sensitive to impurity, and I had previously done a very elaborate job on the compression of iron, with hundreds of measurements, this being basic to all my other compressibilities. The compression of pure iron listed in Table II is taken directly from my previous work.[5]

The numerical results for resistance and compression are given in Table II. No shearing strengths are given, the material being too hard. The general behavior is similar to that in the copper-silicon series. There are no discontinuities or cusps – the regularity of the readings is about the same. The addition of silicon markedly decreases the effect of pressure on resistance. It is perhaps to be anticipated that with greater concentrations the sign of the pressure coefficient may reverse, resistance increasing with pressure instead of decreasing. The compression decreases with increasing silicon by much less than does the resistance, but still the decrease is well beyond the limits of error.

Nickel – Silicon. The metallurgical phase diagrams indicate homogeneous solid solutions of silicon in nickel up to about 10 At per cent silicon, and beyond that, extreme complication. Measurements were made here on five concentrations, varying from 0.08 to 5.8 atomic per cent silicon. I am again indebted for my material to Dr. C. A. Domenicali, who prepared the alloys at the Franklin Institute. They were made in 100 gram ingots by melting in an induction furnace in zirconium oxide crucibles at a vacuum of less than 5 μ. They were then homogenized for 48 hours at 1180° C in a vacuum lower than 1 μ and then cold rolled and swaged to bars approximately 0.125 inch in diameter, in which form they were supplied to me. For the compression measurements pieces 0.75 inch long were cut from these bars without reduction of diameter; they were subjected to a preliminary pressure seasoning

to 30,000. The resistance specimens were rolled to a thickness of 0.002 inch with annealings during and after rolling.

The nickel from which these alloys were made was 99.98% nickel from the International Nickel Company, and the measurements of the effect of pressure on resistance shown in Table III were made on this nickel. The compression measurements of Table III were, however, made on nickel from a different batch, that supplied by Professor Pugh as one of his copper-nickel series. The source of this nickel was also the International Nickel Com-

TABLE III

Nickel – Silicon System

	100 Ni	99.92 Ni .08 Si	99.6 Ni 0.4 Si	98.0 Ni 2.0 Si	96.1 Ni 3.9 Si	94.2 Ni 5.8 Si
$\rho \times 10^{-6}$	6.69	7.38	8.30	13.8	17.7	21.1
Temperature Coefficient	.00611	.00600	.00528	.00334	.00276	.00256
Pressure kg/cm²			Rp/Ro			
0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
5,000	.9902	.9903	.9908	.9930	.9994	.9947
10,000	.9807	.9811	.9819	.9863	.9890	.9898
15,000	.9715	.9721	.9733	.9800	.9837	.9850
20,000	.9626	.9632	.9651	.9740	.9787	.9804
25,000	.9538	.9549	.9569	.9681	.9740	.9760
30,000	.9452	.9466	.9492	.9625	.9694	.9718
40,000	.930	.932	.934	.952	.962	.965
50,000	.917	.919	.920	.942	.955	.957
60,000	.904	.907	.908	.932	.950	.950
70,000	.893	.897	.897	.924	.944	.944
80,000	.883	.888	.887	.916	.939	.938
90,000	.873	.879	.878	.910	.935	.933
100,000	.863	.870	.870	.903	.930	.928
			$-\Delta V/Vo$			
5,000	.00270	.00256	.00272	.00266	.00264	.00255 (f)
10,000	.00524	.00515 (b)	.00544	.00528	.00524	.00528
15,000	.00795 (a)	.00786	.00810 (c)	.00784	.00784 (e)	.00793
20,000	.01065	.01054	.01064	.01037	.01043	.01048 (g)
25,000	.01317	.01299	.01313	.01301 (d)	.01300	.01300
30,000	.01560	.01535	.01558	.01566	.01550	.01543

(a) Cusp at 10,300
(b) Cusp at 8,200; $-\Delta V/Vo = .00416$
(c) Cusp at 15,000
(d) Cusp at 21,700; $-\Delta V/Vo = .01120$
(e) Cusp at 12,000; $-\Delta V/Vo = .00625$
(f) Cusp at 4,700; $-\Delta V/Vo = .00239$
(g) Cusp at 16,500; $-\Delta V/Vo = .00872$

pany, stated by them to be their purest. The presumption would be that it also was of 99.98% purity, but Professor Pugh stated in a letter that "apparently it is of no better than 99.9 purity."

The results for resistance and compression are shown in Table III; the strength was too high for shearing measurements. Previous measurements on pure nickel have shown that its behavior is anomalous. The anomaly is most manifest on the compression, where it displays itself as a cusp, the compressibility being greater at pressures above the cusp, contrary to what might be expected. The occurrence of the anomaly is not clean cut; the pressure at which it occurs and the magnitude of the discontinuity in the slope may be altered by heating or by subjecting to pressure. In previous measurements on a single crystal of presumably high purity,[6] obtained from Dr. Bozorth of the Bell Telephone Laboratory, the location of the cusp finally settled down to 10,500 kg/cm^2 with an upward break in compressibility of 14.5 per cent. Professor Pugh's nickel, after a single preliminary pressure seasoning to 30,000, also showed a cusp in compression at 10,300, with an increase of compressibility of 6.7 per cent. The average compressibility over the 30,000 range of Professor Pugh's nickel was about 3 per cent greater than that of Dr. Bozorth's. In view of the similarity of the results obtained with these two specimens of nickel and the sensitiveness of the results to slight variations in the treatment of the material, compressibility measurements were not repeated on the present nickel of Dr. Domenicali. The compressions of pure nickel shown in Table III are for the material of Professor Pugh.

No anomaly was manifest in the resistance of the present material from Dr. Domenicali. However, another specimen[7] has shown an abrupt numerical decrease of the slope of the curve of resistance versus pressure at 10,000 kg/cm^2 amounting to about 5 per cent of the slope. The present resistance measurements to 30,000 showed a slight hysteresis, amounting at the maximum to a difference between increasing and decreasing readings of one per cent of the change of resistance at 30,000. It would constitute a research in itself to reduce the results on "pure" nickel to complete consistency and reproducibility.

The behavior of the silicon alloys was similar to that of the pure metal. All the compression measurements showed cusps, but

with no consistency in the location of the cusp or in the magnitude of the discontinuity of slope. The behavior of two compositions, 0.08 and 5.8 Si, was best represented by two cusps. The capricious behavior of these anomalies is not surprising in view of the erratic behavior of a single specimen of pure nickel in response to repeated heat treatment and pressure seasoning. The resistances of the alloys, on the other hand, showed no evidence of any cusp. The resistances showed a rather consistent small hysteresis, the width of the hysteresis loop being of the general order of three or four per cent of the maximum change under 30,000. Except for the hysteresis, the resistances were as smooth as usual in the pressure. Because of the nature of the apparatus the hysteresis in resistance in the range above 30,000 could not be determined.

Superposed on the anomalies contributed by the nickel, an inspection of Table III discloses the expected effect of the addition of silicon in that the arithmetical magnitude of the pressure coefficient of resistance diminishes with addition of silicon. The effect of silicon on compression is more difficult to disentangle and more obscure – perhaps on the whole the compression tends to diminish slightly with added silicon.

Copper – Silver. This is the first of four series of alloys which I owe to Dr. T. J. Rowland, the others of the series being Al – Mg, Al – Zn, and Cu – Zn. These alloys were prepared in connection with the thesis work of Dr. Rowland under the direction of Professor N. Bloembergen at Harvard on the general subject of nuclear magnetic resonance in metals and alloys.[8]

The metallurgical phase diagram shows negligible solubility of silver in copper or of copper in silver at room temperature. It is to be expected, therefore, that at room temperature the alloys will be mechanical mixtures of practically pure copper and pure silver.

The silver from which the alloys were prepared is described simply as " c.p.". The copper showed the following "typical analysis." Ag 0.0008; As 0.0002; Bi Tr; Fe 0.001; Mg Nil; Ni 0.0006; Pb 0.0002; Sb 0.0002; Si 0.00025; Sn 0.0003; Te 0.0005; Zn Nil; and traces of Au and Cr. No P, S or Se. The total purity is thus of the order of 99.99. Since I had available 99.999 material, the values for " pure " copper given in the table were obtained from this rather than from the material from which the alloys had been actually prepared.

The material was furnished me in the form of slugs approximately 1 cm in diameter and 2 cm long. From these slugs small pieces were cut for the various measurements. The resistance specimens were rolled to 0.002 inch thickness, with several annealings at red heat during rolling and a final annealing to red heat in a stream of helium followed by immediate exposure to room temperature. The resistance measurements were made without pressure seasoning. The compressibility specimens were swaged, with annealings at red heat, and subjected to a preliminary pressure seasoning at 30,000.

The results are shown in Table IV. The resistance measurements to 30,000 on the 0.5 and 1.0 compositions showed no change of zero on the first application of pressure nor significant hysteresis. The 4.0 composition showed a permanent change of zero of about 2 per cent of the total change of resistance under 30,000, and a hysteresis loop of 4 per cent maximum width; both these effects are well beyond the limits of error. In the table the mean of the resistances with increasing and decreasing pressure are given for the 4 per cent composition. The compression measurements indicated nothing unusual, there being, if anything, less than the normal amount of scatter in the individual readings, with the exception of the 1 per cent composition. Here it is not impossible that there is a cusp with very slight drop of compressibility in the neighborhood of 20,000. The effect is, however, very uncertain, and in the table the mean results with increasing and decreasing pressure have been smoothed over any possible cusp.

The arithmetic magnitude of the pressure coefficient of resistance diminishes with increasing silver content, just as if we were dealing with a solution. A change in the opposite direction is to be expected by the simple rule of addition, since the pressure coefficient of pure silver is greater by a factor of 1.73 (at 30,000) than that of pure copper. The pressure coefficient of the 4 per cent silver composition is as much as 20 per cent less than that of pure copper. The compressibility increases significantly with increasing silver content. This is what would be expected from the additive rule of mixtures, silver being more compressible than copper by about 30 per cent. However, the increase of compressibility on passing from the 0.5 to the 4.0 composition is markedly greater than would be expected from such a rule of mixtures, being 4.5

per cent. (In this comparison the values for pure copper are not strictly comparable, since they were obtained from different material.)

The shearing strength shows no consistent nor certain variation with composition.

Silver – Palladium. The phase diagram shows complete mutual solubility over the entire range of composition.

TABLE IV

Copper – Silver System

	100 Cu	99.5 Cu 0.5 Ag	99.0 Cu 1.0 Ag	96.0 Cu 4.0 Ag
$\rho \times 10^6$	1.69	1.62	1.87	2.15
Temperature Coefficient	.00436	.00404	.00391	.00237
Pressure kg/cm²		Rp/Ro		
0	1.00000	1.0000	1.0000	1.0000
5,000	.99054	.9915	.9919	.9927
10,000	.98195	.9835	.9842	.9859
15,000	.9737	.9760	.9768	.9792
20,000	.9656	.9687	.9697	.9729
25,000	.9579	.9617	.9628	.9669
30,000	.9506	.9549	.9562	.9612
40,000	.939	.943	.946	.953
50,000	.928	.932	.937	.945
60,000	.919	.922	.930	.939
70,000	.911	.914	.923	.933
80,000	.903	.905	.917	.927
90,000	.896	.898	.911	.923
100,000	.890	.891	.906	.919
		$-\Delta V/Vo$		
5,000	.00387	.00366	.00373	.00389
10,000	.00759	.00727	.00735	.00756
15,000	.01117	.01079	.01090	.01120
20,000	.01465	.01420	.01440	.01472
25,000	.01800	.01757	.01778	.01817
30,000	.02119	.02092	.02113	.02185
		Shearing Strength, kg/cm²		
20,000	1,600	1,420	1,510	1,420
40,000	3,420	3,140	3,240	2,810
60,000	5,090	4,700	5,060	4,000
80,000	6,410	6,340	6,900	5,200
100,000	7,510			

TABLE V

Silver – Palladium System

	100 Ag	89.1 Ag 10.9 Pd	79.0 Ag 21.0 Pd	69.3 Ag 30.7 Pd	64.3 Ag 35.7 Pd	59.7 Ag 40.3 Pd	48.9 Ag 51.1 Pd
$\rho \times 10^6$	1.67	6.47	10.74	16.14	19.4	21.4	35.0
Temperature Coefficient	.00381	.00097	.00056	.00041	.00039	.00043	.00025
Pressure kg/cm²				Rp/Ro			
0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
5,000	.9835	.9973	.9986	.9976	.9972	.9967	.9975
10,000	.9677	.9947	.9974	.9952	.9945	.9940	.9951
15,000	.9529	.9922	.9963	.9930	.9918	.9913	.9927
20,000	.9392	.9898	.9954	.9907	.9892	.9886	.9906
25,000	.9263	.9875	.9945	.9887	.9867	.9858	.9884
30,000	.9141	.9853	.9938	.9866	.9844	.9832	.9863
40,000	.889	.983	.993	.985	.980	.979	.983
50,000	.868	.981	.992	.983	.975	.975	.981
60,000	.850	.978	.991	.981	.972	.971	.978
70,000	.835	.977	.991	.980	.969	.968	.976
80,000	.823	.976	.990	.978	.965	.965	.974
90,000	.813	.974	.990	.977	.963	.963	.973
100,000	.806	.973	.989	.976	.960	.961	.972
				$-\Delta V/Vo$			
5,000	.00473	.00445	.00412	.00386	.00376	.00365	.00340
10,000	.00938	.00875	.00815	.00764	.00741	.00716	.00674
15,000	.01385	.01295	.01212	.01135	.01099	.01069	.01002
20,000	.01820	.01707	.01602	.01501	.01450	.01443	.01325
25,000	.02236	.02112	.01978	.01858	.01796	.01744	.01645
30,000	.02619	.02501	.02345	.02207	.02132	.02071	.01953
				Shearing Strength, kg/cm²			
20,000	1,120	1,530	1,770	1,980	1,890	1,650	1,840
40,000	2,050	2,960	3,240	3,520	3,380	3,300	3,500
60,000	2,810	4,300	4,490	4,960	5,310	4,620	4,800
80,000	3,750	5,810	5,900	6,700	7,800	6,690	5,980
100,000		7,330	7,320	8,270			

TABLE V – *Continued*

Silver – Palladium System

44.2 Ag 55.8 Pd	39.3 Ag 60.7 Pd	34.5 Ag 65.5 Pd	29.5 Ag 70.5 Pd	14.5 Ag 85.5 Pd	100 Pd	
38.5	47.0	48.4	46.8	28.4	11.45	$\rho \times 10^6$
.00006	.00006	.00017	.00033	.00110	.00368	Temperature Coefficient
			Rp/Ro			Pressure kg/cm²
1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0
.9977	.9974	.9971	.9964	.9947	.9894	5,000
.9955	.9950	.9942	.9931	.9896	.9793	10,000
.9934	.9926	.9914	.9898	.9846	.9697	15,000
.9914	.9903	.9886	.9866	.9799	.9604	20,000
.9893	.9880	.9859	.9835	.9752	.9517	25,000
.9874	.9859	.9833	.9806	.9709	.9431	30,000
.984	.982	.979	.976	.963	.926	40,000
.980	.979	.975	.973	.956	.910	50,000
.978	.977	.972	.970	.951	.895	60,000
.975	.975	.969	.968	.945	.882	70,000
.972	.973	.966	.965	.940	.870	80,000
.970	.971	.964	.963	.935	.859	90,000
.968	.970	.962	.961	.930	.848	100,000
			$-\Delta V/Vo$			
.00343	.00332	.00322	.00307	.00293	.00267	5,000
.00675	.00657	.00639	.00610	.00583	.00517	10,000
.01002	.00973	.00946	.00907	.00866 (a)	.00761 (b)	15,000
.01322	.01284	.01248	.01201	.01129	.01015	20,000
.01637	.01586	.01542	.01487	.01384	.01273	25,000
.01940	.01877	.01826	.01769	.01637	.01522	30,000
			Shearing Strength, kg/cm²			
1,770	2,240	2,240	2,200	1,980	1,650	20,000
3,400	3,900	4,020	4,000	3,760	3,110	40,000
4,670	4,900	5,200	5,000	4,990	4,310	60,000
5,900	6,250	6,670	6,410	6,350	5,480	80,000
						100,000

(a) Cusp at 15,000

(b) Cusp at 16,500

In the following, measurements were made on eleven compositions distributed over the entire range, which I owe to Mr. A. I. Schindler, who used them in the laboratory of Professor E. M. Pugh at Carnegie Institute of Technology for measurements of the Hall coefficient.[9] This work has not yet been published in detail. The alloys were originally prepared by Baker and Company of Newark to certain nominal compositions. The exact compositions were later determined at the Naval Research Laboratory, to which in the meantime Mr. Schindler had moved, and it is these compositions, changed from weight to atomic per cents, which are given in Table V. A spectroscopic analysis was made of the pure components and the various alloys at the Naval Research Laboratory. The principal impurities in the palladium (of the general order of 0.1 per cent each) were Si, Rh and Al, and the principal impurity in the silver was Cu. The total silver content of the pure silver, determined by wet analysis, was 99.75 per cent.

The material was supplied in the form of small slabs, 1 cm square and 1 mm thick. The resistance specimens were prepared by rolling to about 0.002 inch thickness, with annealing in the air at red heat. The compression specimens were rods approximately 0.75 inch long and 0.06 inch diameter, prepared by forging from pieces approximately $0.40 \times 0.22 \times 0.040$ inch. The first few stages of the forging process were at a red heat, followed by cold hammering with frequent anneals at red heat. The rods were turned to final dimensions and subjected to preliminary pressure seasoning to 30,000.

The resistance measurements went smoothly, with no permanent change of zero after the first application of pressure, and no hysteresis to nearly the sensitivity of the readings, although slight hysteresis was usually detectible. The general behavior is as to be expected; that is, the pressure effect on resistance is smaller in the middle of the concentration range, rising to the pure metals at either end. The effect is far from symmetrical in the composition, however, reaching its maximum at 20 per cent Pd. The sign of the pressure effect is negative throughout, as is normal. At the composition 20 Pd the decrease of resistance under 30,000 is only approximately 1 per cent. In the table the resistances given for the pure metals between 30,000 and 100,000 were not redetermined

on this particular material. The measurements to 30,000 for the present material were in such close agreement with previous measurements[10] on other material that it did not seem worth while to redetermine the resistance for the present material in the range 30,000 to 100,000, but previous measurements to 100,000 were used, applying a slight correction. This correction was plus 0.004 on the relative resistance of silver uniformly over the 30,000 – 100,000 range, and similarly plus 0.001 for palladium.

The compressions, except for one composition, presented no incident, the readings being smooth with no more than the normal scatter and with slight hysteresis, which, however, was no more than found with other materials and may be due to the apparatus. The compressions given in Table V for the pure metals are values previously obtained on other material.[2] The effect of impurity on compression being slight it was thought to be not worth while to redetermine the compressions. Previous measurements of the compression of palladium had disclosed a slight cusp at 16,500. The single exceptional composition referred to above was 14.5 Ag – 85.5 Pd, the composition nearest to pure palladium. This also showed a very slight cusp at 15,000; this cusp was independently found, I having forgotten that pure palladium had a cusp. There was no cusp at higher concentrations of silver, so that the probability is high that the effect is genuine. Both cusps are so small that this independent confirmation is welcome.

In general the shearing strength is greater for intermediate compositions than for the pure metals, as seems natural. Like the resistance, the effect is not symmetrical in the composition, but the maximum shearing strength comes at 35 Pd, against 20 Pd for the maximum effect on resistance.

Aluminum – Copper. The metallurgical phase diagram shows a range of homogeneous solubility of aluminum in copper up to about 20 At % Al. In the following, two compositions, 4.81 and 9.98 At % Al, were investigated. These I owe to Professor Charles S. Smith of the Case Institute of Technology. The alloys were prepared in connection with Professor Smith's program of determining the effect of dilute alloying on the elastic constants of single crystals.[11] I have no specific information as to the materials from which these alloys were formed. The specimens were provided in the form of discs about 2.5 mm thick sliced from a cast

TABLE VI

Copper – Aluminum System

	100 Cu	95.19 Cu 4.81 Al	90.02 Cu 9.98 Al
Density		8.504	8.199
$\rho \times 10^6$	1.69	7.65	10.40
Temperature Coefficient	.00436	.00110	.00092
Pressure kg/cm²		Rp/Ro	
0	1.00000	1.0000	1.0000
5,000	.99054	.9975	.9985
10,000	.98195	.9951	.9971
15,000	.9737	.9927	.9958
20,000	.9656	.9905	.9947
25,000	.9579	.9885	.9936
30,000	.9506	.9866	.9927
40,000	.939	.984	.991
50,000	.928	.982	.990
60,000	.919	.980	.989
70,000	.911	.978	.988
80,000	.903	.977	.987
90,000	.896	.976	.986
100,000	.890	.975	.986
		$-\Delta V/Vo$	
5,000	.00387	.00374	.00371
10,000	.00759	.00738	.00735
15,000	.01117	.01094	.01087
20,000	.01465	.01435	.01431
25,000	.01800	.01769 .01794	.01767 .01814
30,000	.02119	.02121	.02138
		Shearing Strength, kg/cm²	
20,000	1,600	1,250	1,240
40,000	3,420	2,270	2,390
60,000	5,090	3,310	3,480
80,000	6,410	4,370	4,570

ingot 2 cm in diameter. The resistance specimens were formed as usual by rolling to a thickness of approximately 0.002 inch, and annealing. Resistance measurements made to 30,000 with no pressure seasoning showed no permanent change of zero and only insignificant hysteresis, the width of the loop being 2 or 3 per cent of the maximum pressure effect. No episode was shown by the resistance measurements. The compression specimens were formed by hammering, annealing, turning to a length of approximately 0.75 inch and diameter of 0.08 inch, and seasoning by a preliminary application of 30,000. The compression measurements on both compositions showed a reversible discontinuity, indicating a phase change, at about 25,000 kg/cm^2. The magnitude of the discontinuity was about twice as great for the 9.98 composition as for 4.81. In speculating as to the probable nature of this phase change significance must be attached to the fact that doubling the amount of dissolved aluminum leaves the pressure of the discontinuity approximately unaltered, but doubles the magnitude of the discontinuity. At low pressures the effect of the addition of aluminum on compressibility as shown in Table VI is uncertain and in any event slight. At higher pressures and below the transition the compressibility of the alloys seems definitely less than that of pure copper. Professor Smith has inferred by calculations from his dynamically determined elastic constants that at atmospheric pressure the compressibility of the alloys would be greater than that of pure copper.

The effect of aluminum in solution on the pressure effect on resistance is what we have come to regard as " normal," namely a decrease of numerical magnitude of the effect of pressure on resistance. The pressure coefficient of resistance is negative throughout; the effect of dissolved aluminum is only slight.

Shearing strength probably on the whole decreases on addition of aluminum.

Aluminum – Magnesium. The phase diagram indicates that at room temperature magnesium is soluble in aluminum up to something of the order of 2 At %, and that beyond this the system consists of a mechanical mixture with the intermetallic compound Al_3Mg_2.

Six alloys were measured at the aluminum rich end of the series, ranging from 0.64 to 14.3 At % Mg. I owe these to Dr. T. J.

TABLE VII

Aluminum – Magnesium System

	100 Al	99.36 Al .64 Mg	98.83 Al 1.17 Mg	96.93 Al 3.07 Mg	94.85 Al 5.15 Mg	90.86 Al 9.14 Mg	85.7 Al 14.3 Mg
Density	2.690	2.666	2.524?	2.624	2.600	2.564	2.530
$\rho \times 10^6$	2.77	2.86	3.43	4.36	5.68	7.83	10.23
Temperature Coefficient	.00468	.00414	.00389	.00285	.00236	.00173	.00137
Pressure kg/cm²				Rp/Ro			
0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
5,000	.9774	.9802	.9812	.9840	.9862	.9878	.9891
10,000	.9570	.9621	.9640	.9692	.9728	.9758	.9785
15,000	.9380	.9450	.9472	.9555	.9600	.9645	.9685
20,000	.9203	.9285	.9313	.9421	.9475	.9532	.9585
25,000	.9038	.9131	.9165	.9290	.9358	.9423	.9485
30,000	.8880	.9019	.9027	.9167	.9245	.9316	.9392
40,000	.860	.880	.881	.897	.907	.912	.923
50,000	.837	.863	.864	.880	.891	.893	.910
60,000	.817	.845	.850	.865	.875	.876	.899
70,000	.801	.830	.836	.851	.861	.858	.887
80,000	.786	.816	.823	.838	.847	.842	.878
90,000	.774	.804	.813	.825	.833	.826	.869
100,000	.762	.792	.802	.813	.820	.812	.861
				$-\Delta V/Vo$			
5,000	.00668	.00663	.00657	.00678	.00711	.00735	.00738
10,000	.01312	.01299	.01296	.01338	.01404	.01443	.01452
15,000	.01932	.01914	.01923	.01971	.02061	.02109	.02151
20,000	.02520	.02502	.02532	.02589	.02697	.02754	.02911
25,000	.03090	.03072	.03111	.03186	.03297	.03378	.03453
30,000	.03642	.03633	.03648	.03741	.03864	.03954	.04056
				Shearing Strength, kg/cm²			
20,000	1,320	1,350	1,300	1,650	1,700	2,120	2,080
40,000	1,990	2,240	2,640	2,770	3,020	3,070	3,300
60,000	2,840	3,190	3,780	3,820	4,090	3,800	4,170
80,000	4,070	4,250	5,500	5,310	5,550	4,740	5,000

Rowland, who prepared them as part of the program already described under the silver-copper series. The alloys were made from commercial "pure" aluminum of 99.99 purity, and commercial "pure" magnesium, also of 99.99 purity. They were cast into graphite molds, and several were given a forty-hour soak at 450°. The resistance specimens were rolled as usual to a thickness of 0.002 inch, annealed at 440° to 450° and cooled in air. The compression specimens were cut and turned, without swaging or hammering, to a length of 0.50 inch and diameter of 0.136 inch and pressure seasoned by a preliminary exposure to 30,000.

The experimental results are shown in Table VII. The resistance parameters for pure aluminum were redetermined on this present aluminum, since its purity, 99.99, is somewhat higher than that of any aluminum on which I have previously published values.[12] My best previous aluminum had an analysis of 99.966. The higher purity of the present aluminum is attested by its higher temperature coefficient of resistance and numerically larger pressure coefficient of resistance. The fractional decrement of resistance under 30,000 of the present material was 0.1120 against 0.1080 found formerly. The compressions of "pure" aluminum given in the table are, however, for the former 99.966 material, compressions not being sensitive to impurity.

The measurements both for resistance and compression on the alloys went unusually smoothly, without appreciable alterations of zero or hysteresis. Both these effects would be anticipated if pressure were effective in changing the solubility limits, something to be looked for particularly at the lower concentrations. The effect of adding magnesium to aluminum is to diminish the effect of pressure on resistance, as is to be expected. The diminution continues right through the range of concentration studied here. The compression, on the other hand, is at first diminished by the addition of magnesium but there is a reversal between 1 and 3 per cent.

The shearing strength is not greatly affected by the addition of magnesium, with, however, a definite tendency to increase, as might be expected.

Aluminum – Zinc. Eight compositions at the aluminum rich end of the series, ranging up to 15.4 At % zinc, were investigated. For this range of compositions the phase diagram shows, at higher temperatures, a homogeneous solid solution in the lattice of pure

TABLE VIII

Aluminum – Zinc System

	100 Al	99.59 Al 0.41 Zn	99.16 Al 0.84 Zn	98.13 Al 1.87 Zn	97.20 Al 2.80 Zn	96.04 Al 3.96 Zn	93.56 Al 6.44 Zn	90 Al 10 Zn	84.6 Al 15.4 Zn
Density	2.690	2.678	2.717	2.729	2.789	2.838	2.916	3.038	3.205
$\rho \times 10^6$	2.77	3.17	3.11	3.66	3.57	4.14	4.09	4.72	6.72
Temperature Coefficient	.00468	.00458	.00429	.00401	.00359	.00322	.00299	.00250	.00194
Pressure kg/cm²					Rp/Ro				
0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
5,000	.9774	.9799	.9814	.9833	.9863	.9890	.9909	.9953	1.0006
10,000	.9570	.9616	.9645	.9675	.9734	.9790	.9826	.9910	1.0014
15,000	.9380	.9440	.9473	.9527	.9612	.9696	.9748	.9870	1.0025
20,000	.9203	.9274	.9319	.9388	.9500	.9606	.9677	.9834	1.0038
25,000	.9038	.9116	.9172	.9257	.9392	.9523	.9610	.9801	1.0053
30,000	.8880	.8966	.9032	.9135	.9292	.9445	.9547	.9772	1.0067
40,000	.860	.872	.881	.892	.911	.930	.946	.973	1.010
50,000	.837	.850	.861	.873	.896	.917	.942	.971	1.014
60,000	.817	.831	.844	.856	.885	.907	.936	.968	1.019
70,000	.801	.815	.827	.841	.875	.897	.933	.967	1.025
80,000	.786	.800	.811	.828	.866	.888	.928	.966	1.031
90,000	.774	.785	.797	.814	.856	.881	.924	.965	1.038
100,000	.762	.772	.783	.802	.849	.873	.922	.964	1.046
					$-\Delta V/Vo$				
5,000	.00668	.00663	.00657	.00648	.00660	.00669	.00669	.00660	.00675
10,000	.01312	.01308	.01299	.01278	.01302	.01320	.01317	.01308	.01335
15,000	.01932	.01938	.01926	.01902	.01926	.01950	.01941	.01941	.01968
20,000	.02520	.02538	.02529	.02511	.02529	.02559	.02544	.02550	.02571
25,000	.03090	.03117	.03108	.03087	.03147	.03138	.03120	.03132	.03153
30,000	.03642	.03681	.03648	.03633	.03639	.03668	.03666	.03696	.03702
					Shearing Strength, kg/cm²				
20,000	1,320	1,420	1,530	2,190	2,300	1,860	2,100	2,290	2,120
40,000	1,990	2,760	2,600	3,870	3,800	3,300	3,160	3,780	3,350
60,000	2,840	3,760	3,620	5,270	5,020	4,390	4,250	5,200	4,580
80,000	4,070	5,500	5,020	6,850	6,630	6,450	5,810	6,850	5,880
100,000						8,900	7,320	8,250	7,080

aluminum, which, however, on dropping temperature to room temperature, completely unmixes into pure aluminum and pure zinc.

The alloys were provided by Dr. T. J. Rowland, who prepared them as part of his program already described. The purity of the aluminum from which the alloys were made has already been described in connection with the aluminum-magnesium series. The zinc showed a typical analysis of: As 4×10^{-6}, Cd 5×10^{-5}, Cu 5×10^{-5}, Fe 4×10^{-4}, Pb 2×10^{-4}, Sn 10^{-5}. This makes the total impurity of the order of 0.001 per cent.

The alloys as received from Dr. Rowland were ostensibly in the solid solution phase, having been quenched. The resistance specimens were prepared as usual by rolling to a thickness of 0.002 inch, with several annealings at 400° during rolling, followed after rolling by a final quench to room temperature from 400° C. The compression specimens were cut from the ingot as received, and subjected to a preliminary seasoning application of 30,000.

The results are given in Table VIII. The measurements of resistance went with unusual smoothness, with no hysteresis or permanent alteration of zero. In fact, if it were not due to error arising from uncertainty as to the exact composition, another significant figure would have been justified in the changes of resistance tabulated up to 30,000. The resistance measurements therefore gave no evidence whatever of incomplete internal equilibrium or of precipitation of zinc induced by pressure. The compression measurements, on the other hand, exhibited considerable hysteresis. They did not, however, show any permanent alteration of zero, which would have been an indication of precipitation of zinc.

The effect of addition of zinc on the pressure coefficient of resistance follows the conventional pattern, the pressure effect becoming less with added zinc. Here the effect is carried to a greater extreme than usual, the pressure coefficient reversing sign from negative to positive for the greatest concentration of zinc, 15.4 At %. The effect of dissolved zinc on compression is slight; at first the compression diminishes slightly with added zinc, but there is a reversal in the neighborhood of 2 per cent zinc, the compression of the higher compositions being somewhat greater than that of pure aluminum. This may well be a specific effect of the zinc atom, the compressibility of pure zinc being markedly greater than that of pure aluminum.

The shearing strength at first rises with addition of zinc, with probably a reversal and maximum in the neighborhood of 2 per cent.

Gold – Copper. The phase diagram at low temperatures of a few hundred degrees is complicated by the presence of the compounds Cu_3Au, Cu_3Au_2, and CuAu. These compounds undergo transitions from their ordered to their disordered states on raising temperature, and the attainment of equilibrium between the states may be slow and show hysteresis. It is to be expected, therefore, that at room temperature the behavior will not be particularly clean cut.

In the following, measurements were made on two series of alloys from two different sources, at the copper rich end of the series, running up to a maximum of 27.8 At % Au. The first batch consisted of six compositions ranging from 2 to 27.8 At % Au, obtained from Professor Foster C. Nix at the University of Pennsylvania. These alloys were made from copper and gold both described as "spectroscopically pure," but without further analysis. The alloys were supplied in single crystal form in cylindrical slugs approximately 3 mm in diameter and 1 cm long. They had been extensively annealed after casting – the 2% composition at 850° C in vacuum for 24 hours, and the other compositions at temperatures from 875° to 900° in vacuum for 48 hours. Pieces were cut from these slugs and rolled for the resistance measurements to a thickness of 0.002 inch. After and during rolling they were annealed at red heat in a stream of helium, and allowed to cool of themselves to room temperature. Measurements were made on these six alloys of resistance to 30,000 and to 100,000 and of shearing strength. After these measurements had been completed a second series of alloys was placed at my disposal by Mr. William G. Johnston of the General Electric Company. There were seven in this series, ranging in composition from 1 to 25 At % Au. Mr. Johnston has not yet published his results on these alloys. They were prepared from 99.999 copper from the American Smelting and Refining Company and from 99.999 gold from Sigmund Cohn, Inc. No further chemical analysis was attempted. The following description of the method of preparation was supplied by Mr. Johnston. "The pure metals were cut into small pieces and mixed to the desired compositions in batches of about 100 grams. The alloys were melted under vacuum in a graphite crucible, swaged to

0.1 inch diameter, cut into small pieces, and remelted. This procedure was repeated twice, but the alloys remained inhomogeneous as indicated by resistivity measurements along the length of the 0.1 inch diameter wires. The alloys were then sealed in quartz capsules under vacuum. While the alloys were molten the capsules were agitated vigorously for two minutes. The alloys were allowed to solidify in less than two minutes. The resulting alloys were homogeneous. The resistivities were measured at room temperature after the alloys were swaged and drawn from 0.5 inch diameter to about 0.1 inch diameter. The alloys have not received high temperature anneals, which may be desirable in order to eliminate short range fluctuations in composition." The specimens for my resistance measurements were rolled as usual in several stages to a thickness of 0.002 inch, with heating between the stages to a dull red in air. After the final rolling, the five compositions through 17% Au were sealed in an evacuated glass tube, heated to 350° C in an electric furnace, and cooled to room temperature with the furnace over night. These five compositions should therefore be in the ordered condition, if indeed there is any difference between the ordered and disordered condition for this range of composition. The two compositions 20 and 25% Au were measured in two heat treatments, since it is for these compositions that the greatest effect of ordering or disordering is to be anticipated. One heat treatment consisted of an anneal at 350° like the other compositions. The second heat treatment was a water quench from 500° C, which should give the disordered state. The compressions were measured on rods in the diameter of approximately 0.1 inch as received, cut to a length of 0.75 inch. They were subjected to the same heat treatments as the resistance specimens. Shearing strength was not measured on the specimens from Mr. Johnston, there being no reason to anticipate any difference as compared with the other series, and experimental error in shearing strength being comparatively high.

Selected results are shown in Table IX, in which are given specific resistances, temperature coefficients and pressure effects on resistance and the compressions of the seven alloys of Johnston (nine columns in all with the two different heat treatments), and shearing strength and densities for the six compositions of Nix. In addition to the results here given in Table IX, there are specific

TABLE IX

Copper – Gold System

	100 Cu	99 Cu 1 Au	97 Cu 3 Au	93 Cu 7 Au	89 Cu 11 Au	85 Cu 15 Au	83 Cu 17 Au	80 Cu 20 Au annealed	80 Cu 20 Au quenched	75 Cu 25 Au annealed	75 Cu 25 Au quenched
$\rho \times 10^6$	1.69	2.47	3.28	5.60	7.65	8.78	9.59	10.77	9.91	7.40	11.94
Temperature Coefficient	.00436	.00313	.00221	.00136	.00103	.00082	.00077	.00077	.00072	.00152	.00065
Pressure kg/cm²					Rp/Ro						
0	1.00000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.00000	1.0000
5,000	.99054	.9944	.9968	.9993	1.0002	1.0007	1.0008	1.0016	1.0007	1.00068*	1.0007
10,000	.98195	.9891	.9939	.9986	1.0004	1.0014	1.0016	1.0032	1.0013	1.00051	1.0014
15,000	.9737	.9839	.9912	.9981	1.0007	1.0022	1.0025	1.0048	1.0019	1.00091	1.0021
20,000	.9656	.9788	.9886	.9976	1.0010	1.0029	1.0034	1.0064	1.0026	1.00135	1.0028
25,000	.9579	.9740	.9863	.9972	1.0014	1.0037	1.0043	1.0081	1.0035	1.00181	1.0036
30,000	.9506	.9695	.9841	.9968	1.0018	1.0046	1.0053	1.0099	1.0043	1.00229	1.0046
40,000	.939	.963	.981	.9981	1.0030	1.0074	1.0085	1.0138	1.0067	1.0041	1.0080
50,000	.928	.957	.979	.9998	1.0050	1.0106	1.0129	1.0183	1.0099	1.0061	1.0126
60,000	.919	.952	.977	1.0022	1.0072	1.0144	1.0178	1.0228	1.0143	1.0088	1.0178
70,000	.911	.948	.975	1.0052	1.0102	1.0190	1.0228	1.0275	1.0197	1.0119	1.0243
80,000	.903	.945	.973	1.0087	1.0134	1.0236	1.0277	1.0325	1.0259	1.0154	1.0315
90,000	.896	.942	.972	1.0125	1.0171	1.0284	1.0331	1.0379	1.0327	1.0189	1.0400
100,000	.890	.939	.971	1.0178	1.0211	1.0332	1.0366	1.0431	1.0407	1.0227	1.0494
					$-\Delta V/Vo$						
5,000	.00387	.00354	.00357	.00354	.00332	.00339	.00344	.00388	.00344	.00328	.00334
10,000	.00759	.00707	.00707	.00702	.00661	.00668 .00698	.00683	.00671	.00685	.00655	.00664
15,000	.01117	.01053 .01092	.01052	.01043	.01009	.01026	.01015	.00995	.01017 .01043	.00974	.00989
20,000	.01465	.01431	.01385 .01469	.01379 .01427	.01355	.01341	.01340 .01382	.01313	.01368	.01291	.01309
25,000	.01800	.01767	.01767	.01736	.01699	.01655	.01700	.01626	.01715	.01613	.01625
30,000	.02119	.02095	.02059	.02035	.02034	.01961	.02009	.01934	.02018	.01910	.01936
	98 Cu 2 Au	95 Cu 5 Au	88.3 Cu 11.7 Au	82.5 Cu 17.5 Au	80.3 Cu 19.7 Au	72.2 Cu 27.8 Au					
Density	9.190	9.540	10.455	11.023	11.299	12.522					
			Shearing Strength, kg/cm²								
20,000	1,540	1,650	1,560	1,650	1,510	1,600					
40,000	3,450	3,760	3,600	3,800	3,420	3,520					
60,000	4,870	5,450	5,350	5,440	5,200	5,200					

resistances, temperature coefficients of resistance, and resistances to 100,000 for Nix's alloys. It seemed hardly worth while to reproduce these in detail, but Figure 1 gives an idea of the relative behavior. Here are plotted the temperature coefficients and the relative changes of resistance produced by 30,000 kg/cm^2 for the two series of Nix and Johnston. The agreement for the two series is as good as could be expected except for the greatest concentrations of gold. Here the marked difference between the annealed and the quenched condition of Johnston's alloys indicates the importance of the order – disorder transition for these compositions, and suggests that reproducible results will be obtained only by meticulously controlling the heat treatment so as to obtain true equilibrium conditions, which certainly was not done here.

The specific resistances given in the table for the compositions through 17% Au are those determined by Johnston, his dimensions being more favorable to accuracy than mine. His measurements were made at room temperature ($28 \pm 1°$ C) and have been reduced to 0° C with my values for the temperature coefficients. The specific resistances for the two compositions 20 and 25% Au are mine, measured on rolled material 0.002 inch thick, and are of somewhat inferior accuracy because of difficulty of exactly determining the thickness. It was nevertheless necessary to use these values rather than Johnston's because of the indefiniteness of his heat treatment. It will be noticed that the specific resistance varies with heat treatment for these two compositions by an amount far beyond any possible experimental error. The specific resistances of Nix's alloys, determined by me, lie on the curve with Johnston's within the limits of error, except at the highest composition, 27.8 Au, for which the value lies on a linear prolongation of the curve at lower concentrations, with no suggestion of the marked disturbance in specific resistance shown by both heat treatments of the 20 and 25% compositions.

The pressure effect on resistance presents an extreme example of the sort of behavior so often found. The pressure coefficient not only diminishes in magnitude but actually reverses in sign with increasing gold content, the compositions beyond 5% Au showing a slight increase of resistance under pressure. This increase was so slight as to present a special problem as to how best to adjust the measurements above 30,000 so as to agree with those below

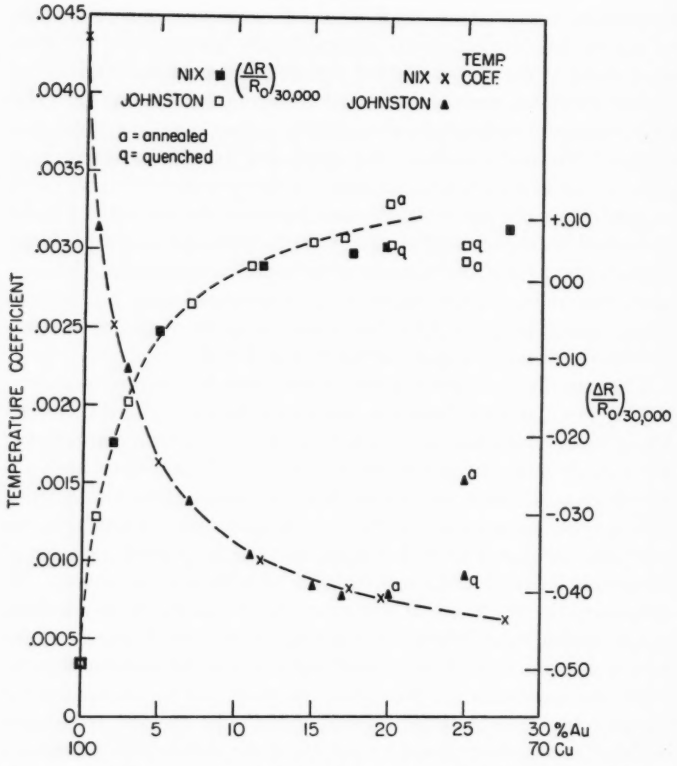

Figure 1. The temperature coefficient of resistance and the decrement of relative resistance at 30,000 kg/cm² for copper-gold alloys from two different sources.

30,000. The measurements above 30,000 suffer from the disadvantage that pressures are not truly hydrostatic, whereas the measurements below 30,000 may be accepted at their face value since the pressure is hydrostatic. The method of adjustment which I have hitherto applied in all normal cases has been to take the decrements of relative resistance from 30,000 as zero and apply to these uniformly that percentage correction which would bring the resistance change between 20,000 and 30,000 into agreement with that

obtained with the 30,000, truly hydrostatic, apparatus. But in the present situation this method is not applicable, because often the 100,000 measurements show an initial decrease of resistance, reversing to an increase at some pressure perhaps in the neighborhood of 50,000 or 60,000, whereas actually the resistance should increase with pressure over the entire range, as given by the 30,000 apparatus. No percentage correction, obviously, can change a decrease into an increase. The course was therefore adopted of rotating the entire curve of resistance versus pressure as a rigid whole about the point at 30,000 as fixed point, by such an angle as to bring the resistance change between 20,000 and 30,000 into agreement with that given by the 30,000 apparatus. This procedure amounts to assuming that the non-hydrostatic effect, whatever it is that produces the initial decrease rather than an increase of resistance, remains linear in pressure over the entire pressure range. This is almost certainly not the case, but I can see no more plausible way of handling the situation at present. This procedure has the advantage of preserving the general shape of the curve, which is always concave upward, agreeing with most other cases which show a positive pressure coefficient of resistance. The plausibility of the method is enhanced by the fact that it gives a roughly regular progression of resistance changes with composition at the higher pressures. In any event, the effects are small, the maximum change of resistance at 100,000 being about 5 per cent. It cannot be claimed, however, that this 5 per cent is itself known with any considerable percentage accuracy.

The sign of the pressure effect as finally calculated by this procedure reverses for two of the compositions: for Johnston's 7% Au between 30,000 and 40,000, and for Nix's 5% Au at approximately the same pressure. It would have been desirable if this reversal could have been observed in the range of the 30,000 apparatus, for which the results are above question. It cannot be rigorously maintained, therefore, that this reversal is actually true for any of the compositions, although I do not believe there is any serious doubt of it.

Unlike the resistance measurements, the compressions of most of the compositions show a discontinuity in the range below 30,000. This is probably indicative of some change in the order – disorder situation. The pressures at which these discontinuities

occur do not, however, show any consistent correlation with composition. It is probable that much more elaborate heat treatment than any attempted here would be necessary to obtain consistent results or results whose significance would be clear. The situation here seems to be typical of that often found, namely that the compression is a more sensitive indicator of internal changes than the resistance; the reverse might perhaps have been thought to be more probable.

The shearing measurements showed no incidents suggesting internal rearrangements. It is probable that during shearing the material is so highly deformed that all distinction disappears between an ordered and a disordered arrangement. In general, there seems to be a slight tendency to an increase of shearing strength with increasing gold content; this is in the direction to be expected.

Cobalt — Iron. Only a single composition of this series was measured, Fe 40.9 — Co 59.1 At %. I owe the specimen to Professor Nix. The phase diagram indicates at this composition a solid solution in alpha iron of the phase of cobalt stable at atmospheric pressure between approximately 500 and 1100° C. The alloy as received had been melted in vacuum in an induction furnace, annealed in hydrogen for 24 hours at 900°C, and cooled with the furnace. The compression specimen was turned from the slug as received, without further heat treatment. The resistance specimens were rolled to a thickness of 0.0025 inch and annealed at red heat in the air. No shearing measurements were attempted because of the high strength.

The results for change of resistance and for compression are given in Table X. Resistance decreases slightly under pressure, with decreasing curvature at the higher pressures, as is normal. The resistance was smooth in pressure, with no discontinuities either of absolute value or of slope, but with a definite and consistent hysteresis. The maximum width of the hysteresis loop was 6.5 per cent of the maximum pressure effect. The table gives the mean with increasing and decreasing pressure. The mean compressibility is slightly less than that of pure iron. There are two distinct cusps on the curve of compression, at 5,000 and at 22,400 kg/cm^2, at each of which the compressibility *increases*. At the 22,400 cusp the increase is sufficient to make the compressibility above 22,400 slightly greater than that of iron in the same pressure range. Here again

we have abnormalities revealed by the compression to which the changes of resistance are insensitive.

Copper – Gallium. The phase diagram shows, at room temperature, a range of homogeneous solid solution of gallium in copper up to about 20 atomic per cent gallium. At higher temperatures and concentrations the diagram becomes extremely complicated.

In the following, measurements are presented on two alloys, of 1.58 and 4.15 At % Ga, obtained from Professor Charles S. Smith of the Case Institute of Technology. I have no information about the purity of the materials from which the alloys were formed.

TABLE X

Cobalt – Iron System

	100 Co	59.06 Co 40.04 Fe	100 Fe
Density		8.32	
$\rho \times 10^6$		5.33	11.3
Temperature Coefficient		.00414	.00585
Pressure kg/cm²		Rp/Ro	
0	1.000	1.0000	1.0000
5,000		.9979	.9884
10,000	.991	.9959	.9773
15,000		.9941	.9666
20,000	.983	.9925	.9562
25,000		.9909	.9464
30,000	.976	.9895	.9368
40,000	.970	.987	.920
50,000	.965	.985	.906
60,000	.961	.984	.893
70,000	.958	.982	.881
80,000	.955	.981	.870
90,000	.953	.980	.861
100,000	.951	.979	.852
		$-\Delta V/Vo$	
5,000	.00253	.00271*	.00289
10,000	.00504	.00553	.00575
15,000	.00760	.00829	.00856
20,000	.01086	.01099	.01133
22,400		.01227*	
25,000	.01253	.01367	.01406
30,000	.01492	.01639	.01676

* Cusp at this pressure

They were supplied in the form of discs sliced transversely from the cast ingot, approximately 2 cm in diameter and 3 mm thick. From these, small pieces were cut and rolled as usual, with annealings at red heat, for the resistance measurements. The compression specimens were prepared by hammering, interspersed with annealings at dull red, to rods of approximately 2 cm length and 3 mm diameter, which were then pressure seasoned to 30,000 before measurement.

TABLE XI

Copper – Gallium System

	100 Cu	98.42 Cu 1.58 Ga	95.85 Cu 4.15 Ga
Density		8.873	8.856
$\rho \times 10^6$	1.69	4.63	7.64
Temperature Coefficient	.00436	.00173	.00115
Pressure kg/cm²		Rp/Ro	
0	1.00000	1.0000	1.0000
5,000	.99054	.9951	.9959
10,000	.98195	.9904	.9920
15,000	.9737	.9858	.9882
20,000	.9656	.9813	.9846
25,000	.9579	.9771	.9811
30,000	.9506	.9729	.9778
40,000	.939	.966	.972
50,000	.928	.960	.968
60,000	.919	.956	.963
70,000	.911	.951	.959
80,000	.903	.947	.956
90,000	.896	.944	.953
100,000	.890	.941	.951
		$-\Delta V/Vo$	
5,000	.00387	.00373	.00376
10,000	.00759	.00735	.00740
15,000	.01117	.01086	.01091
20,000	.01465	.01419	.01429
25,000	.01800	.01762	.01762
30,000	.02119	.02086	.02082
		Shearing Strength, kg/cm²	
20,000	1,600		1,580
40,000	3,420		2,820
60,000	5,090		3,900
80,000	6,410		5,090

The results are shown in Table XI. All the phenomena, resistance, compression and shearing, the latter on one composition only, were smooth in pressure, with no discontinuities of slope or of absolute value. The compression showed a slight hysteresis, but probably no more than is inherent in the apparatus. There was also small and consistent hysteresis in the resistance, probably more than can be explained instrumentally. The maximum width of the hysteresis loop was not more than 2 per cent of the pressure effect

TABLE XII

Copper – Germanium System

	100 Cu	98.97 Cu 1.03 Ge	98.29 Cu 1.71 Ge
Density		8.897	8.881
$\rho \times 10^6$	1.69	5.88	8.59
Temperature Coefficient	.00436	.00142	.00100
Pressure kg/cm²		Rp/Ro	
0	1.00000	1.0000	1.0000
5,000	.99054	.9956	.9963
10,000	.98195	.9913	.9927
15,000	.9737	.9872	.9892
20,000	.9656	.9833	.9859
25,000	.9579	.9795	.9826
30,000	.9506	.9760	.9795
40,000	.939	.970	.974
50,000	.928	.965	.969
60,000	.919	.960	.965
70,000	.911	.956	.961
80,000	.903	.953	.958
90,000	.896	.950	.955
100,000	.890	.948	.953
		$-\Delta V/Vo$	
5,000	.00387	.00371	.00362
10,000	.00759	.00732	.00714
15,000	.01117	.01081	.01060
20,000	.01465	.01420	.01397
25,000	.01800	.01760	.01729
30,000	.02119	.02085	.02053
		Shearing Strength, kg/cm²	
20,000	1,600		1,890
40,000	3,420		3,170
60,000	5,090		4,470
80,000	6,410		5,800

at 30,000, or 0.05 per cent on the total resistance. The mean of resistance with increasing and decreasing pressure is given in the table.

The effect of pressure on resistance diminishes with addition of gallium, as we have come to expect. The compressibility on the whole diminishes slightly with increasing gallium content. The shearing strength is not greatly affected, but definitely diminishes.

Copper – Germanium. The phase diagram shows solid solution of germanium in copper up to about 10 At % Ge; beyond that the diagram is complicated. However, the diagram does not appear to have been worked out for temperatures below 500° C, so that there is no basis for judging whether slow reactions are to be anticipated at room temperature or not.

Two alloys were investigated here, of 1.03 and 1.71 atomic per cent germanium, both obtained from Professor Smith at the same time as the copper-gallium alloys. The form of the material and the method of preparation for the measurements were the same as for the copper-gallium alloys.

The results are shown in Table XII. There were no irregularities or notable features in the behavior, and in general the same remarks apply as for the copper-gallium alloys.

Copper – Nickel. The phase diagram shows homogeneous solid solutions over the entire composition range. At 25° C those compositions richer in nickel than 70 At % are ferromagnetic, those poorer than 70% in nickel are paramagnetic. Six compositions, ranging from 40 to 90 At % Ni, were measured, which I owe to the courtesy of Professor Emerson M. Pugh at Carnegie Institute of Technology. He in turn had obtained the four compositions 90, 80, 70 and 60 Ni from the International Nickel Company. This company also supplied a specimen of pure nickel, said by them to be the purest they had available. However, Professor Pugh remarked that apparently it was not better than 99.9%. The temperature coefficient of this nickel, as determined by me, was 0.00569 between room temperature and 0° C. I also had on hand another piece of nickel supplied to Dr. C. A. Domenicali by the International Nickel Company, and said by them to be of 99.98 purity. The temperature coefficient of this, as determined by me over the same range of temperature, was 0.00611, materially higher than the value for nickel from the same company supplied by

Professor Pugh. I therefore used the values obtained with Domenicali's nickel for the resistance parameters to be listed in Table XIII for "pure nickel." In addition to the four compositions just mentioned, Professor Pugh supplied me with 50 and 40% nickel, which he had obtained from the Westinghouse Research Laboratories. No statement is available with regard to the presumptive purity of these two compositions. These copper-nickel alloys had been used for measurements under Professor Pugh's direction of the Hall effect. Part of this work has been published.[13] Further measurements by Philip Cohen have been published in Tech. Rep. No. 1 of Contract NONR –760104, Office of Naval Research, dated June 30, 1955, and are also projected for publication in the Physical Review. Floyd Allison has further data scheduled for publication under the same ONR contract and presumptively the Physical Review.

The material was supplied in the form of cast slabs approximately 1.5 cm square and 5 mm thick. Resistance specimens were prepared as usual by rolling to a thickness of 0.002 inch, with annealings at red heat during and after rolling. The compression specimens were forged rods 0.75 inch long and 0.15 inch in diameter, annealed during and after forging, and subjected to a preliminary seasoning application of 30,000.

The results are shown in Table XIII. The values for "pure" nickel are the same as already given under the nickel-silicon series. It will be recalled that the values for resistance are for another specimen of nickel of greater purity. The compressions given in the table are, however, for the same grade of nickel as that from which the other alloys with copper were prepared (Professor Pugh's). Although not given in the table, measurements of resistance were also made on the same nickel of Professor Pugh. There was no evidence of a cusp near 10,000, such as had been shown by another sample of nickel of presumptively about the same purity (temperature coefficient between room temperature and 0° C of the present nickel being 0.00569 against 0.00573 of the former material exhibiting the cusp), but there was smooth and consistent hysteresis, the maximum difference between readings with increasing and decreasing pressure being 2.3 per cent of the change of resistance at 30,000. No cusps or discontinuities were found in the resistance of any of the copper-nickel alloys. How-

TABLE XIII

Copper – Nickel System

	100 Cu	60 Cu 40 Ni	50 Cu 50 Ni	40 Cu 60 Ni	30 Cu 70 Ni	20 Cu 80 Ni	10 Cu 90 Ni	100 Ni
$\rho \times 10^6$	1.69	49.2	61.1	51.1	48.2	30.3	19.0	6.69
Temperature Coefficient	.00436	−.00045	+.000050	.000133	.00227	.00273	.00314	.00611
Pressure kg/cm²				Rp/Ro				
0	1.00000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
5,000	.99054	.9975	.9978	.9976	.9968	.9955	.9939	.9902
10,000	.98195	.9951	.9956	.9953	.9937	.9912	.9881	.9807
15,000	.9737	.9928	.9935	.9931	.9907	.9871	.9826	.9715
20,000	.9656	.9906	.9916	.9909	.9877	.9831	.9773	.9626
25,000	.9579	.9884	.9897	.9888	.9848	.9792	.9723	.9538
30,000	.9506	.9863	.9878	.9867	.9821	.9755	.9674	.9452
40,000	.939	.983	.985	.983	.977	.969	.959	.930
50,000	.928	.979	.982	.980	.973	.964	.952	.917
60,000	.919	.977	.979	.977	.969	.959	.945	.904
70,000	.911	.974	.977	.975	.966	.954	.938	.893
80,000	.903	.972	.975	.973	.963	.950	.933	.883
90,000	.896	.970	.974	.971	.960	.946	.927	.873
100,000	.890	.969	.972	.970	.958	.942	.922	.863
				$-\Delta V/Vo$				
5,000	.00387	.00319	.00313	.00299	.00294	.00288	.00267	.00270
10,000	.00759	.00637	.00621	.00594	.00584	.00569	.00553	.00524
15,000	.01117	.00945	.00924	.00885	.00870	.00848	.00830	.00795*
20,000	.01465	.01251	.01223	.01172	.01153	.01122	.01098	.01065
25,000	.01800	.01555	.01519	.01455	.01432	.01390	.01367	.01317
30,000	.02119	.01853	.01800	.01733	.01706	.01655	.01627	.01560
				Shearing Strength, kg/cm²				
20,000	1,600	1,700						
40,000	3,420	3,780						
60,000	5,090	6,150						
80,000	6,410	8,300						

* Cusp at 10,300

ever there was consistent hysteresis, similar to that for "pure" nickel, becoming less with increasing copper content, and practically vanishing with 50 and 60 per cent copper. No cusps or discontinuities were found in the compression of any of the alloys except for an obscure and uncertain discontinuity near 25,000 for the 50 – 50 composition; this was smoothed over in constructing the table. However, the compression did show hysteresis, which paradoxically increased in magnitude with increasing copper content. The maximum width of the loop for the composition 60 Cu – 40 Ni was about 2 per cent of the compression at 30,000.

The general effect of alloying on the pressure effect on resistance is as usual – the magnitude of the decrease of resistance brought about by pressure decreases from both ends of the series on departing from the pure metals. It reaches its maximum decrement at the composition 50 – 50. This is *not* the composition at which the temperature coefficient reaches its minimum value, this occurring in the copper rich end of the series. The compressions, on the other hand, diminish monotonically from that of pure copper to that of pure nickel.

The shearing strength was determined for only a single composition, 60Cu – 40Ni, the strength of the higher compositions being so high as to endanger the apparatus. For this one composition the strength is greater than that of pure copper, as would be expected.

Copper – Zinc. The phase diagram at room temperature consists of a homogeneous alpha phase up to about 40 atomic per cent zinc, a mixed alpha and beta′ phase between approximately 40 and 47 per cent zinc, and a homogeneous beta′ phase between approximately 47 and 50 per cent zinc. The designation beta is applied to the phase into which beta′ transforms above 460° C. The compositions studied here lay within the range from 0 to 50 per cent zinc.

Eight compositions were measured, which I owe to Dr. T. J. Rowland. Of these, seven were in the range between 0.5 and 20 At % Cu, and thus were the homogeneous alpha phase. The eighth composition was 52.7 Cu – 47.3 Zn, and thus is the pure beta′ phase. This composition was investigated in both the annealed and the quenched conditions in order if possible to obtain information about the unstable beta phase. The other compositions should be unaffected by heat treatment as far as phase changes go.

TABLE XIV

Copper – Zinc System

	100 Cu	99.5 Cu 0.5 Zn	99.0 Cu 1.0 Zn	98.75 Cu 1.25 Zn	97.5 Cu 2.5 Zn	95.41 Cu 4.59 Zn
Density	8.915	8.923	8.883	8.947[2]	8.785	
$\rho \times 10^6$	1.69	1.86	2.52	2.44	2.72	2.81
Temperature Coefficient	.00436	.00402	.00364	.00353	.00305	.00257
Pressure kg/cm²			Rp/Ro			
0	1.00000	1.0000	1.0000	1.0000	1.0000	1.0000
5,000	.99054	.9918	.9927	.9927	.9939	.9948
10,000	.98195	.9837	.9857	.9860	.9882	.9897
15,000	.9737	.9762	.9789	.9795	.9824	.9848
20,000	.9656	.9690	.9724	.9731	.9769	.9802
25,000	.9579	.9619	.9661	.9670	.9717	.9756
30,000	.9506	.9552	.9599	.9609	.9667	.9713
40,000	.939	.944	.949	.950	.958	.964
50,000	.928	.934	.939	.940	.950	.958
60,000	.919	.925	.931	.932	.942	.951
70,000	.911	.916	.924	.925	.935	.946
80,000	.903	.908	.918	.918	.930	.941
90,000	.896	.901	.912	.911	.924	.936
100,000	.890	.895	.907	.906	.920	.933
			$-\Delta V/Vo$			
5,000	.00387		.00366	.00359		.00373
10,000	.00759		.00721	.00710		.00737
15,000	.01117		.01073	.01056		.01097
20,000	.01465		.01413	.01393		.01446
25,000	.01800		.01750	.01726		.01787
30,000	.02119		.02059	.02049		.02120
			Shearing Strength, kg/cm²			
20,000	1,600	1,480	1,650	1,770	1,650	1,300
40,000	3,420	3,070	3,400	3,760	3,780	2,620
60,000	5,090	4,250	4,600	5,900	5,750	3,560
80,000	6,410	5,550	5,970	8,170	8,150	4,560
100,000	7,510			10,280	10,500	

TABLE XIV – *Continued*

Copper – Zinc System

95 Cu 5 Zn	90 Cu 10 Zn	87.43 Cu 12.57 Zn	80 Cu 20 Zn	52.7 Cu(a) 47.3 Zn	52.7 Cu(b) 47.3 Zn	
8.210	8.565		8.649			Density
3.09	4.50	6.31	6.13	5.85	4.60	$\rho \times 10^6$
.00253	.00201	.00156	.00177	.00279	.00319	Temperature Coefficient
			Rp/Ro			Pressure kg/cm²
1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0
.9946	.9961	.9981	.9971	.9919	.9901	5,000
.9897	.9926	.9963	.9944	.9842	.9809	10,000
.9850	.9891	.9946	.9919	.9768	.9723	15,000
.9807	.9859	.9931	.9895	.9699	.9642	20,000
.9764	.9827	.9916	.9872	.9634	.9565	25,000
.9723	.9797	.9902	.9850	.9572	.9490	30,000
.965	.975	.988	.981	.947	.936	40,000
.959	.970	.987	.977	.938	.926	50,000
.953	.967	.985	.974	.930	.917	60,000
.949	.964	.984	.971	.924	.909	70,000
.945	.961	.983	.969	.918	.902	80,000
.942	.958	.983	.968	.913	.896	90,000
.939	.956	.983	.968	.908	.890	100,000
			$-\Delta V/Vo$			
	.00384	.00405	.00401	.00420	.00424	5,000
	.00758	.00801	.00789	.00841	.00845	10,000
	.01126	.01188	.01172	.01272	.01270	15,000
	.01479	.01569	.01551	.01711	.01695	20,000
	.01830	.01938	.01920	.02138(c)	.02154(d)	25,000
	.02172	.02301	.02297	.02471	.02478	30,000
			Shearing Strength, kg/cm²			
2,050	1,700	1,630	2,310			20,000
4,250	3,820	2,980	4,370			40,000
6,500	5,550	4,020	6,250			60,000
8,940	7,220	5,000	8,150			80,000
10,760	9,100		9,800			100,000

(a) Quenched from dull red

(b) Annealed at 410° C.

(c) Cusp at 24,000; $-\Delta V/Vo = .02068$

(d) Cusp at 25,000

The zinc from which the alloys were prepared has already been described under the Al – Zn series and the copper under the Ag – Cu series.

In addition to the eight compositions obtained from Dr. Rowland results are also shown in Table XIV for two compositions, 4.59 and 12.57 At % Zn, obtained from Professor Charles S. Smith. I have no detailed information about the copper and zinc from which these two alloys were prepared.

The resistance specimens were prepared as usual by rolling pieces cut from the cast ingots, and annealing by heating to redness in the air clamped between iron plates, and cooling slowly in the air with the plates. The compression specimens were cylinders 0.75 inch long and 0.16 inch in diameter, prepared by cold hammering, with annealings, of pieces cut from the castings. They were pressure seasoned to 30,000 before measurements. The 52.7 Cu – 47.3 Zn composition was measured in both the annealed and the quenched condition, as already described.

The results are shown in Table XIV. The values for " 100 Cu " were obtained on 99.999 material from two different sources as already described. All the measurements went smoothly, without discontinuities or cusps or significant hysteresis, except the compression measurements for 52.7 Cu – 47.3 Zn. This showed a cusp in the compression curve near 25,000 in both the quenched and the annealed conditions. The compression at pressures higher than the cusp is discontinuously less than below the cusp.

The general behavior of the resistance is as to be expected; the decrease of resistance produced by pressure becomes numerically less as the concentration of zinc increases. The single composition 87.4 Cu – 12.5 Zn of Professor Smith lies out of line in this respect with the other compositions of Dr. Rowland in that its pressure effect is abnormally small. The other composition of Professor Smith, however, is in line with the compositions of Dr. Rowland. The compound 52.7 Cu – 47.3 Zn is decidedly out of line with what would be expected from extrapolation of the results for the homogeneous alpha phase, the effect of pressure being very much larger. The pressure effects on the quenched and the annealed states of the compound do not differ greatly, but the difference is well beyond experimental error. The pressure effect is greater for the annealed condition, as is also the temperature coefficient of resistance.

The initial effect of adding zinc in dilute solution is to decrease the compressibility, but at higher concentrations the compressibility increases, becoming greater than that of pure copper. This is doubtless a specific effect of the zinc, which is much more compressible than pure copper, compressibilities having a rough tendency to add. Again the compressibility of Professor Smith's 87.4 Cu – 12.6 Zn is out of line, being too high. His other composition is in line. The cusp in the compressibility of the compound has already been mentioned. In general, the two states of the compound have very nearly the same compressibility; more careful repetition would be necessary to establish that the difference given in the table is beyond experimental error.

The shearing strengths show greater irregularity than usual. On the whole the strength tends to increase with addition of zinc.

Nickel – Manganese. Measurements were made on essentially a single composition of approximately 71 At % Ni. This composition can, by proper heat treatment, be obtained either in a disordered paramagnetic condition or in an ordered ferromagnetic condition. The principal interest of the present measurements was to find whether there is a difference in the behavior under pressure of the two configurations. I owe the specimens to the kindness of Professor Nix. Both were melted in an induction furnace in an atmosphere of hydrogen and homogenized in hydrogen at 1100° C. The ferromagnetic form was hot forged at 900° C and cooled with the furnace from this temperature. The paramagnetic form received a slight amount of hot forging at 900° C and was then quenched from this temperature. For my measurements the compression specimens were ground from the pieces as received, without further heat treatment, but pressure seasoned to 30,000 before measurement. The small pieces for resistance measurements to 100,000 were also ground from the ingot without heat treatment. The resistance specimens for the measurements to 30,000 were rolled to a thickness of approximately 0.007 cm. One was annealed at a low red heat and cooled in the air to obtain the ferromagnetic condition, and the other was quenched from 900° C after rolling to obtain the paramagnetic condition.

The results are shown in Table XV. The resistance of the ferromagnetic condition in the range to 30,000 was without appreciable hysteresis or permanent displacement of zero. The resistance

of the disordered condition, on the other hand, showed marked hysteresis and permanent displacement of zero in the 30,000 range. The readings with increasing and decreasing pressure lay on smooth curves within the sensitiveness of the readings (1% of the change of resistance). In the table the values in the left hand column are for increasing pressure and in the right for decreasing. For both conditions the readings from 30,000 to 100,000 were adjusted so as to join smoothly with the readings to 30,000 with increasing pressure. The number of significant figures given for

TABLE XV

Nickel – Manganese System

	100 Ni	71.3 Ni 28.7 Mn ordered	71.0 Ni 29.0 Mn disordered	
Density		8.106		
$\rho \times 10^6$	6.69	88.4	76.5	
Temperature Coefficient	.00611	.00031	.00097	
Pressure kg/cm²		Rp/Ro		
0	1.0000	1.0000	1.0000	.9976
5,000	.9902	.9987	.9992	.9963
10,000	.9807	.9977	.9989	.9949
15,000	.9715	.9963	.9965	.9940
20,000	.9626	.9951	.9949	.9933
25,000	.9538	.9940	.9933	.9927
30,000	.9452	.9930	.9922	
40,000	.930	.991	.990	
50,000	.917	.989	.988	
60,000	.904	.988	.986	
70,000	.893	.986	.985	
80,000	.883	.985	.984	
90,000	.873	.984	.983	
100,000	.863	.984	.983	
		$-\Delta V/Vo$		
5,000	.00270	.00331	.00361	
10,000	.00524	.00656	.00718	
15,000	.00795 (a)	.00975	.01057 (b)	
20,000	.01065	.01292	.01378	
25,000	.01317	.01605	.01697	
30,000	.01560	.01911	.02006	

(a) Cusp at 10,300

(b) Cusp at 12,600; $-\Delta V/Vo = .00900$

the resistance between 30,000 and 100,000 is not justified by the absolute accuracy, but is necessary to show the shape of the curves, the absolute change of resistance being small. The compression measurements on the ordered material show nothing striking – if anything, there was somewhat more hysteresis than usual with the compression measurements. The compressibility of the disordered condition, on the other hand, is initially markedly higher than for the ordered condition, but there is a cusp at 12,600, and above that nearly the same compressibility as for the ordered condition with the result that the total change of volume under 30,000 is not very different for the two conditions. What slight difference there is is in the direction of a higher compressibility for the disordered condition, which is perhaps what might be expected. The compression of the disordered condition does not show significantly greater hysteresis than the ordered.

Discussion and Summary

On the whole, the alloys examined in this paper have shown much less in the way of new episodes than the alloys of the earlier papers. This is doubtless connected with the higher melting points of the metals involved here and the consequent greater sluggishness to internal change. The only example of a permanent change produced by application of pressure has been a displacement of the zero of resistance by 0.24% for the disordered state of 71 Ni – 29 Mn. This possibly may be connected with a partial return toward order. Again no changes have been found that can be associated with changes of solubility limits under pressure – this would seem to be a very rare phenomenon. It is true that many examples of hysteresis have been found, but these have usually been very slight, and probably indicate nothing more than the effect of slight mechanical strains incident to the application of pressure. Such strains are to be expected at the grain boundaries even if the grains themselves are cubic and therefore isotropically compressible.

There are very few examples of first order discontinuities such as would indicate reversible phase changes. The resistance of the annealed condition of 75 Cu – 25 Au shows a small discontinuity at 5,000 kg/cm^2. The volumes of many of the Cu – Au series show

small reversible discontinuities at pressures roughly in the neighborhood of 15,000, but varying irregularly with composition. This discontinuity occurs for compositions with gold content of 1, 3, 7, 15, 17 and 20 (the latter in the quenched condition only) per cent. The effect occurs at too small concentrations of gold to make an explanation in terms of an order – disorder transition plausible.

Cusps, or discontinuities in the tangent, are more common. These cusps are all on the curves of volume versus pressure and not on the resistance curves, a somewhat surprising state of affairs. Pure nickel has a cusp in the compressibility which varies in location and magnitude in a way which I have not succeeded in definitely correlating with the details of its treatment. This same cusp turns up with all the silicon alloys of Ni up to 5.8% Si, the details of the occurrence of the cusp again varying apparently capriciously in the neighborhood of 15,000. The composition 5.8% Si has two cusps. The disordered state of the alloy 71 Ni – 29 Mn also has a cusp; there would seem to be no necessity that this be the same cusp as that of pure nickel. Pure palladium has a cusp on the compressibility at about 15,000. The same cusp apparently occurs with the 85 Pd – 15 Ag alloy, but disappears at higher silver concentrations. The alloy 59 Co – 41 Fe has cusps on the compression at 5,000 and 22,400; the pure metals have no cusps. Finally, the alloy 52.7 Cu – 47.3 Zn has cusps on the compression near 25,000 in both the beta and beta′ forms (quenched and annealed). These two forms would thus appear to be very similar.

Consider now the more normal phenomena with no discontinuities. All the alloys of this paper satisfy the nearly universal rule that addition of an alloying element to a pure metal increases algebraically the pressure coefficient of resistance. In the case of normal metals with negative pressure coefficient this means a numerical decrease of the pressure coefficient on alloying. This rule is almost as universal as the rules that the temperature coefficient decreases and the specific resistance increases on alloying. It suggests itself to search for a correlation between the pressure coefficients and the temperature coefficients. To this end one may plot against the temperature coefficient, as given in the various tables, the proportional change of resistance produced by 30,000 kg/cm^2, this latter being perhaps the most accurate way of representing

the pressure effect with a single parameter. The family of curves obtained in this way are in the first place approximately straight lines over nearly the entire range of values studied here, in spite of the fact that the temperature coefficient of resistance, for example, is linear in the composition over only a comparatively small range. The slope of all the lines of the family has the same sign in virtue of the rules already mentioned, that is, temperature coefficient and absolute value of the pressure effect increase together. The slopes of the various lines vary, however, over a range of three or more, with the result that an extrapolation of the lines would, for some of the systems, indicate a reversal of sign of the temperature coefficient while the pressure coefficient is still normal, and for others a reversal of sign of the pressure effect while the temperature coefficient is still positive. In two of the series reversals of sign of the pressure effect were actually realized, in the copper-gold and the aluminum-zinc series. The latter series exhibits by far the greatest variation of the pressure effect. The most marked departure from linearity in the plot of temperature versus pressure coefficient is shown by the copper-nickel series — starting from the pure nickel end this heads toward a reversal of pressure coefficient before reversal of temperature coefficient, but changes direction on approaching the copper rich end, and finishes with actual reversal of the temperature coefficient while the pressure effect is still normal.

The most extensive information given by this paper is with regard to alloys of copper, there being seven of these, with silicon, gallium, germanium, silver, aluminum, gold, and zinc. The system copper-nickel is not included here because no compositions were available at the copper rich end. Of these seven series the curves of pressure versus temperature effect for the first three, silicon, gallium and germanium, practically coincide with each other and are linear over the entire length. Of the others, the slope of the curve for the silver-copper series is less, and the others greater, that of the gold-copper series being so much greater as to carry into a reversal of sign of the pressure effect. It has not been unusual in previous theorizing with regard to the resistance of alloys to seek for some connection with the molecular weight of the alloying metal, and indeed series have been found in which the depression of the temperature coefficient has been proportional

to the molecular weight of the alloying element. However, the example here presented of the seven copper series shows that any attempt to extend such considerations to the pressure effect on resistance can have no very extensive range of applicability.

The remarks just made apply only within the range of a single homogeneous phase; naturally one can not expect regularities shown within the domain of one phase to carry over to other phases.

Passing now to a consideration of the compressions, the range of numerical values is much less than for the changes of resistance, so that any generalizations must be less striking and more subject to experimental error. There is one regularity, however, that holds in so many cases that it must be significant. The first effect of adding an alloying metal in dilute solution is to diminish the compressibility, taking as the best measure of the compressibility the compression under 30,000 kg/cm^2. The only exception is presented by Al – Zn, but here the effects are unusually small and the exception occurs only at the greatest dilution, and it is not impossible that experimental error is responsible. Another apparent exception is Cu – Al, but here the direct comparison at 30,000 is vitiated by the occurrence of a first order transition; at pressures below the transition the generalization holds. One is reminded of Tammann's observation that the compressibility of dilute aqueous solutions is almost always less than that of pure water. Tammann's explanation, which does not hold without exception, was that the dilute solution acts effectively like pure water under an external pressure equal to the "internal pressure" exerted by the solute, the compressibility of pure water decreasing with increasing pressure. Something analogous may be happening with these alloys. It is to be noticed that the effect does not necessarily persist at higher concentrations, but if the dissolved metal is intrinsically more compressible than the solvent metal, the compression will reverse and increase at higher concentrations, as seems natural.

The shearing strength phenomena offer no obvious generalizations. No examples were found for this series of alloys, as has sometimes been found for others, of exceptional points on the shearing curve which might indicate some internal change not suggested by the other phenomena. All the shearing curves found here were smooth. Perhaps on the whole the shearing strength

tends to increase on adding dissolved metal, but the effect is not large nor the tendency certain.

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Effects of Pressure on Binary Alloys

VI

Systems for the Most Part of Dilute Alloys of High Melting Metals

By P. W. Bridgman

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Introduction

This sixth and last paper of the series[1] is concerned, like the fifth, with alloys which I owe to the kindness of other workers. These were obtained from three sources. First, there are ten systems, embracing 43 individual specimens, which I owe to Mr. Frederick A. Otter, Jr., who prepared them at the Research Laboratory of the Franklin Institute. These systems include as the major component silver, gold, or copper, to which have been added small amounts, usually in the solubility range, of chromium, manganese,

palladium, or platinum. Second, are four alloys of silver with comparatively small amounts of cadmium, indium, magnesium and zinc. These were prepared by Dr. Roger Bacon, under the direction of Professor Charles S. Smith of the Case Institute of Technology, in connection with his thesis. The particular interest of these four specimens lies in the cubic compressibility, especially the value at atmospheric pressure extrapolated from the results at higher pressures. At the Case Institute the conventional elastic constants were determined at atmospheric pressure. From these constants the initial cubic compressibility can be calculated by the canonical formulas of elasticity theory. It seems to be the general rule, however, that the compressibility calculated in this way has an accuracy inferior to the directly measured value. These present pressure measurements permit a comparison of the directly measured with the calculated compressibility. Thirdly, there are nine alloys which were prepared at M. I. T. by Mr. L. Kaufman and Mr. B. S. Lement under the direction of Professor Morris Cohen. These include five nickel-iron alloys, ranging from 9.6 to 37.0 At % nickel, one iron-carbon alloy, measured in two heat treatments, and finally three non-binary alloys, essentially invars to which have been added different amounts of carbon. Professor Cohen was interested to find the effect of the added carbon, which is the reason for including these three non-binary alloys in this series.

The scope of the measurements is the same as in the preceding papers of the series: effect of pressure on resistance in two ranges, to 30,000 and to 100,000 kg/cm^2; linear (and by calculation, cubic) compressibility to 30,000; plastic flow strength to 80,000; and specific resistance and temperature coefficient of resistance between 0° C and room temperature at atmospheric pressure.

A few items of general technique require mention. Most of the specimens were furnished in the form of wires of the order of 1 mm in diameter. For the measurements of resistance under pressure it was necessary to roll the wire to a thickness of the order of 0.002 inch. This has the disadvantage that the specific resistance calculated from the measured resistance has an appreciable error because of error in the thickness, which was measured with a micrometer reading only to 0.0001 inch. In order, therefore, to obtain higher accuracy on the specific resistance, measurements were made on

the original wire, before rolling. The temperature coefficient was also measured on the wire at the same time, being determined from three measurements of the resistance, at room temperature, at 0° C, and again at room temperature.

The diameter of the majority of the wires was so small that it was anticipated that the longitudinal stability would be insufficient under the usual conditions of measurement with the "lever piezometer". The modification was therefore introduced of measuring the compressibility of a bundle of three lengths, mounted in parallel like a single specimen. The bundle of three specimens had an outside diameter of 0.19 inch, the maximum diameter that the piezometer will accept. The result of this arrangement was the average compression of the three specimens. The internal evidence is that the arrangement was satisfactory.

The pressure measurements with the 30,000 apparatus did not run as smoothly as usual. Since this was the last expected set of measurements with this apparatus, I tried to avoid the construction of new pressure vessels, and thus was led to use old pressure vessels, some of which had been discarded a number of years ago because of suspicious behavior. It turned out that these suspicions were justified, leak being more frequent than usual. Mostly I was able to get by with lapping out the bore of the vessels to a larger diameter, but at the end all the available old cylinders were used up. There was a final crisis when one cylinder developed a catastrophic leak due to an open fissure completely penetrating the wall at about mid-length of the cylinder. It was the first time in my experience of over twenty years that a cylinder reinforced by the external conical support of the 30,000 apparatus had overtly failed. But it appears that many of these cylinders, while they may not fail overtly, do develop minute cracks at the inner surface which are the occasion of leak after many applications of pressure, and that an experimenter in this field would advisedly be prepared to discard his pressure vessels without trying to squeeze the last possible use out of them.

Fortunately the crisis presented by the fracture of the cylinder could be met by remachining a cylinder which had been used only a few times and which had been prepared with a different design for a different purpose. This was the cylinder with which I had measured the absolute linear compressibility of iron.[2]

Another crisis was presented by the explosive failure of one of the four terminal insulating plugs. A comparatively short length of this plug projects from the cylinder without lateral support, so that this short length experiences the full compressive stress of 30,000 kg/cm^2. This particular plug failed, after long use, aggravated perhaps by an accidental slight increase in the length of the unsupported part, and this failure was accompanied by complete destruction of the most recent and accurate lever piezometer.[3] Fortunately an earlier piezometer was still available, and with this the last 25 out of 58 compressibility measurements were made. The regularity of the individual measurements is distinctly less with the old piezometer, but enough readings were taken so that the average should not be much inferior to that given with the better piezometer, particularly when it is considered that the absolute compressibility of the alloys of this paper is high, making the need for the better piezometer less acute.

The detailed presentation of data now follows. Compositions are given in atomic per cents, as in the rest of the series. This has sometimes demanded the recalculation by me of compositions given to me in weight per cents. None of the alloy systems measured here included the major metal in the pure state. The parameters for the pure metals given in the following tables were taken from my earlier work, and are mostly the same as in the fifth paper of this series.

Detailed Data

Silver – Manganese. Five alloys were available, containing up to 14.59 At % Mn, obtained from Otter. According to Hansen's Handbook the alloy system in the neighborhood of 950° C consists of an alpha phase, with the same lattice as pure silver, reaching from pure silver up to 33% Mn, and beyond this, up to pure manganese, of a mechanical mixture of the lattices of pure manganese and the alpha phase. Measurements apparently have not been made at lower temperatures; the presumption is that the maximum concentration of manganese studied here, 14.59%, is still in the region of homogeneous solid solution.

The results are collected in Table I. All three phenomena, resistance change, volume change, and flow strength, were smooth in pressure, exhibiting neither cusps nor other discontinuities. The

most notable feature of these alloys is the positive pressure coefficient of resistance. Up to 30,000, particularly at the higher concentrations, the relation between pressure and change of resistance is almost exactly linear. This suggests the possibility of using these alloys for a resistance pressure gauge, replacing manganin. The highest composition has a coefficient somewhat higher than that of manganin, and its temperature coefficient is low enough to make it perhaps worth considering. At pressures above 30,000 and

TABLE I

Silver – Manganese System

	Ag 100	Ag 98.07 Mn 1.93	Ag 96.15 Mn 3.85	Ag 92.43 Mn 7.57	Ag 88.86 Mn 11.14	Ag 85.41 Mn 14.59
$\rho \times 10^6$	1.67	4.84	7.44	13.10	18.90	24.70
Temperature Coefficient	.00381	.00134	.00064	.00027	.000100	.000022
Pressure kg/cm²			Rp/Ro			
0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
5,000	0.9835	1.0031	1.0086	1.0123	1.0130	1.0148
10,000	0.9677	1.0065	1.0175	1.0248	1.0262	1.0296
15,000	0.9529	1.0101	1.0265	1.0374	1.0394	1.0444
20,000	0.9392	1.0140	1.0355	1.0498	1.0526	1.0592
25,000	0.9263	1.0181	1.0446	1.0623	1.0657	1.0741
30,000	0.9141	1.0225	1.0539	1.0746	1.0788	1.0889
40,000	0.889	1.0310	1.0750	1.0989	1.1035	1.1158
50,000	0.868	1.0414	1.0968	1.1237	1.1262	1.1408
60,000	0.850	1.0566	1.1193	1.1491	1.1493	1.1644
70,000	0.835	1.0755	1.1417	1.1734	1.1704	1.1869
80,000	0.823	1.0963	1.1642	1.1982	1.1924	1.2091
90,000	0.813	1.1200	1.1887	1.2252	1.2143	1.2332
100,000	0.806	1.1475	1.2167	2.2526	2.2375	1.2581
			$-\Delta V/Vo$			
5,000	.00473	.00489	.00506	.00506	.00506	.00514
10,000	.00938	.00961	.01001	.00995	.00996	.01012
15,000	.01385	.01414	.01469	.01462	.01467	.01498
20,000	.01820	.01853	.01913	.01911	.01914	.01961
25,000	.02236	.02283	.02334	.02344	.02355	.02406
30,000	.02619	.02699	.02744	.02762	.02782	.02841
			Shearing Strength, kg/cm²			
20,000	1,120	1,460	1,720	1,840	2,060	2,080
40,000	2,050	2,710	2,760	2,950	3,190	3,290
60,000	2,810	3,540	3,430	3,650	3,990	3,900
80,000	3,750	4,400	4,170	4,250	4,620	4,600

up to 100,000, the resistance versus pressure curves of the lower compositions are concave upward, and that of the higher compositions concave downward. Interpolation suggests that the resistance of an alloy containing approximately 1.3% Mn would be unaffected by pressure. It would be interesting to investigate more dilute alloys in order to determine whether the pressure coefficient is linear in concentration at low concentrations – it apparently approaches an asymptotic value at high concentrations.

TABLE II

Silver – Platinum System

	Ag 100	Ag 99.44 Pt 0.56	Ag 98.88 Pt 1.12	Ag 98.32 Pt 1.68	Ag 97.75 Pt 2.25
$\rho \times 10^6$	1.67	2.27	2.96	3.71	4.43
Temperature Coefficient	.00381	.00275	.00212	.00177	.00146
Pressure kg/cm²			Rp/Ro		
0	1.0000	1.0000	1.0000	1.0000	1.0000
5,000	0.9835	0.9888	0.9915	0.9933	0.9948
10,000	0.9677	0.9784	0.9838	0.9870	0.9899
15,000	0.9529	0.9686	0.9766	0.9811	0.9852
20,000	0.9392	0.9593	0.9698	0.9756	0.9808
25,000	0.9263	0.9505	0.9634	0.9706	0.9767
30,000	0.9141	0.9421	0.9574	0.9658	0.9729
40,000	0.889	0.927	0.946	0.958	0.967
50,000	0.868	0.913	0.937	0.952	0.961
60,000	0.850	0.902	0.929	0.947	0.957
70,000	0.835	0.892	0.922	0.942	0.953
80,000	0.823	0.883	0.916	0.938	0.950
90,000	0.813	0.876	0.912	0.935	0.948
100,000	0.806	0.870	0.908	0.933	0.946
			$-\Delta V/Vo$		
5,000	.00473	.00487	.00481	.00487	.00476
10,000	.00938	.00953	.00942	.00950	.00942
15,000	.01385	.01400	.01391	.01397	.01379
20,000	.01820	.01837	.01823	.01829	.01811
25,000	.02236	.02267	.02245	.02253	.02234
30,000	.02619	.02679	.02658	.02663	.02643
			Shearing Strength, kg/cm²		
20,000	1,120	1,420	1,630	1,650	1,840
40,000	2,050	2,670	2,750	2,910	2,980
60,000	2,810	3,610	3,420	3,690	3,700
80,000	3,750	4,640	4,180	4,870	4,890

The compressibility increases somewhat with increasing amounts of manganese. Since the compressibility of pure manganese is 70 per cent greater than that of pure silver, this is not surprising.

On the whole the shearing strength increases with increasing content of manganese, as would be expected in a solution, but the increase is not a smooth function of concentration. At the lower concentrations and higher pressures the shearing curve is concave upward, but at higher concentrations the curvature reverses.

Silver – Platinum. Four alloys were available from Otter, containing up to 2.25 per cent Pt. The phase diagram, according to both Hansen and Metals Handbook, consists at the silver rich end of a homogeneous solution up to approximately 20 per cent Pt at 400°. The phase diagram is not known for lower temperatures, but it would be surprising if the maximum composition studied here, 2.25% Pt, were not in the homogeneous range.

The results are shown in Table II. None of the phenomena showed discontinuity or irregularity of any kind. The resistance of all the alloys decreases with increasing pressure over the entire pressure range. The numerical magnitude of the decrease becomes less with increasing platinum content, which is the normal direction of variation. The compressibility is slightly and irregularly higher with increasing platinum content, doubtless a result of the opening of the lattice structure by the addition of a foreign atom.

The shearing strength increases somewhat with addition of platinum. At low pressures all shearing curves are concave toward the pressure axis, but with increasing pressure there is a reversal of curvature, the magnitude of the reversal increasing with platinum content.

Gold – Silver. Four alloys were available from Otter, with increasing silver content up to 5.35% Ag. It seems to be generally accepted that the gold-silver system consists of a homogeneous solid solution over the entire composition range. The results are given in Table III. The specific resistance of pure gold listed in the table was taken from Metals Handbook; I have no value of my own.

The resistance varies smoothly with pressure. Resistance decreases with increasing pressure, the magnitude of the decrease decreasing with increasing silver content. This is the almost universal direction of variation.

The changes of volume, unlike the changes of resistance, were

not entirely featureless in pressure. The two lower concentrations, 0.91 and 1.77% Ag, exhibited a distinct cusp near 20,000, the compressibility above 20,000 being discontinuously less than below. This cusp was particularly clean cut for the lowest concentration, with no uncertainty from experimental irregularities in the individual readings. For the 1.77 concentration the experimental irregularities were somewhat greater, making the existence of the

TABLE III

Gold – Silver System

	Au 100	Au 99.09 Ag 0.91	Au 98.23 Ag 1.77	Au 96.42 Ag 3.58	Au 94.65 Ag 5.35
$\rho \times 10^6$	2.19	2.51	2.76	3.10	3.74
Temperature Coefficient	.00391	.00329	.00306	.00256	.00244
Pressure kg/cm²			Rp/Ro		
0	1.0000	1.0000	1.0000	1.0000	1.0000
5,000	0.9849	0.9877	0.9887	0.9894	0.9910
10,000	0.9707	0.9757	0.9778	0.9795	0.9826
15,000	0.9571	0.9644	0.9675	0.9700	0.9744
20,000	0.9441	0.9538	0.9578	0.9608	0.9668
25,000	0.9316	0.9434	0.9486	0.9521	0.9594
30,000	0.9194	0.9333	0.9400	0.9439	0.9526
40,000	0.896	0.916	0.926	0.930	0.940
50,000	0.874	0.902	0.913	0.919	0.930
60,000	0.855	0.889	0.901	0.909	0.921
70,000	0.840	0.878	0.891	0.900	0.914
80,000	0.829	0.869	0.882	0.893	0.908
90,000	0.821	0.860	0.874	0.886	0.902
100,000	0.816	0.852	0.867	0.879	0.897
			$-\Delta V/Vo$		
5,000	.00281	.00296	.00296(b)	.00296	.00297
10,000	.00558	.00586	.00584	.00588	.00589
15,000	.00831	.00872	.00871	.00874	.00878
20,000	.01101	.01164(a)	.01154(c)	.01156	.01162
25,000	.01367	.01430	.01427	.01433	.01441
30,000	.01626	.01699	.01697	.01709	.01715
			Shearing Strength, kg/cm²		
20,000	1,350	1,650	1,510	1,560	1,530
40,000	2,760	2,690	2,500	2,600	2,580
60,000	4,320	3,520	3,320	3,610	3,470
80,000	6,420	5,150	4,850	5,250	5,040

(a) Cusp at 19,000; $-\Delta V/Vo = .01099$
(b) Irregular values at lower pressures
(c) Cusp at 20,000

cusp less unequivocally certain. The 1.77 concentration also showed comparatively large disturbances at pressures below 7,500 kg/cm^2, both with increasing and decreasing pressure, including a permanent change of length of the order of 0.01 per cent. This was smoothed out in the results given in the table. The two higher concentrations, 3.58 and 5.35 per cent, show no trace of the cusp at 20,000. The individual points for the 3.58 composition show no more than the experimental irregularity to be expected, as indicated by measurements on other systems. The same is true for the 5.35 composition except for the points below 5,000, where there is a disturbance reminiscent of that for the 1.77 composition, but much less in amount, the permanent change of length being only one fifth as great.

There is no reason to think that these obscure volume anomalies are not real (the measurements were made with the better piezometer), although the significance may not be clear. There are other examples of systems with sluggish internal changes, which sometimes occur and sometimes do not.

The shearing strength of the alloys is somewhat greater than that of pure gold at the lower pressures and less at the higher pressures. All of the shearing curves show the pronounced abnormal reversal of curvature at high pressures shown by pure gold, the shearing strength finally rising more and more rapidly with increasing pressure.

Gold — Manganese. Four compositions, running up to 18.64% Mn, were available from Otter. With regard to the 18.64 composition Otter makes the remark, "Possible ordering or change of phase around 300-400° C". The phase diagram of Hansen shows a homogeneous solid solution in the gold lattice up to about 30% Mn at the melting temperature, with no relevant observations at lower temperatures.

The results are shown in Table IV. For the four compositions studied here resistance *increases* smoothly with pressure, with no irregularity. Particularly is this true for the 18.64 composition, no single reading for which deviates from a smooth curve by more than the sensitiveness of a single reading, which amounts to 1/700 of the maximum change. At the lower concentrations there is a slight but definite upward curvature of the curve of resistance versus pressure, which reverses to downward curvature at the higher con-

centrations. The positive coefficient of these alloys of manganese with gold is distinctly less than for the alloys with silver at the corresponding concentrations, making the gold alloys less suitable for a pressure gauge.

Interpolation suggests that the pressure effect on resistance should vanish at a concentration of 2.5% Mn. At a pressure of 100,000 the total increase of resistance is roughly independent of concentration in the experimental range, a result of the continued

TABLE IV

Gold – Manganese System

	Au 100	Au 96.50 Mn 3.50	Au 93.17 Mn 6.83	Au 86.99 Mn 13.01	Au 81.36 Mn 18.64
$\rho \times 10^6$	2.19	10.5	18.2	32.4	45.8
Temperature Coefficient	.00391	.00068	.00035	.000153	.000092
Pressure kg/cm²			Rp/Ro		
0	1.0000	1.0000	1.0000	1.0000	1.0000
5,000	0.9849	1.0030	1.0046	1.0066	1.0084
10,000	0.9707	1.0060	1.0093	1.0131	1.0168
15,000	0.9571	1.0091	1.0140	1.0196	1.0251
20,000	0.9441	1.0121	1.0188	1.0261	1.0334
25,000	0.9316	1.0153	1.0235	1.0326	1.0416
30,000	0.9194	1.0186	1.0283	1.0391	1.0497
40,000	0.896	1.024	1.0389	1.051	1.065
50,000	0.874	1.032	1.049	1.062	1.078
60,000	0.855	1.041	1.061	1.073	1.089
70,000	0.840	1.053	1.074	1.084	1.100
80,000	0.829	1.070	1.088	1.098	1.111
90,000	0.821	1.093	1.105	1.112	1.123
100,000	0.816	1.123	1.126	1.128	1.135
			$-\Delta V/Vo$		
5,000	.00281	.00297	.00298	.00322	.00327
10,000	.00558	.00589	.00594	.00636	.00646
15,000	.00831	.00862	.00884	.00942	.00957
20,000	.01101	.01162	.01168	.01237	.01263 .01326
25,000	.01367	.01439	.01451	.01527	.01620
30,000	.01626	.01715	.01727	.01811	.01908
			Shearing Strength, kg/cm²		
20,000	1,350	1,720	1,530	1,790	1,730
40,000	2,760	2,740	2,830	3,180	3,260
60,000	4,320	3,920	4,090	4,400	4,940
80,000	6,420	5,690	6,060	5,750	6,500

upward curvature of the curves for low concentrations and the downward curvature of the curves for high concentrations.

The compressibility measurements of the three lower concentrations showed no certain feature greater than the experimental irregularity of the individual points, which was somewhat greater than usual, except for a definite hysteresis between increasing and decreasing pressure. This was greater than normal, rising to a maximum of 1 per cent of the total change of length for the 13.01 com-

TABLE V

Gold – Palladium System

	Au 100	Au 99.19 Pd 0.81	Au 98.18 Pd 1.82	Au 96.99 Pd 3.01	Au 96.01 Pd 3.99
$\rho \times 10^6$	2.19	2.44	2.80	3.25	3.59
Temperature Coefficient	.00391	.00339	.00291	.00245	.00224
Pressure kg/cm²			Rp/Ro		
0	1.0000	1.0000	1.0000	1.0000	1.0000
5,000	0.9849	0.9871	0.9885	0.9895	0.9900
10,000	0.9707	0.9748	0.9775	0.9794	0.9804
15,000	0.9571	0.9631	0.9670	0.9698	0.9713
20,000	0.9441	0.9519	0.9569	0.9606	0.9625
25,000	0.9316	0.9412	0.9472	0.9519	0.9542
30,000	0.9194	0.9310	0.9378	0.9435	0.9462
40,000	0.896	0.913	0.923	0.930	0.934
50,000	0.874	0.897	0.910	0.918	0.924
60,000	0.855	0.884	0.899	0.907	0.915
70,000	0.840	0.872	0.888	0.898	0.907
80,000	0.829	0.862	0.879	0.891	0.901
90,000	0.821	0.853	0.871	0.885	0.895
100,000	0.816	0.846	0.864	0.879	0.890
			$-\Delta V/Vo$		
5,000	.00281	.00294	.00289	.00288	.00288
10,000	.00558	.00594	.00575	.00573	.00572
15,000	.00831	.00870	.00856	.00852	.00856
20,000	.01101	.01149	.01134	.01131	.01132
25,000	.01367	.01425 .01422	.01410	.01406	.01412 .01406
30,000	.01626	.01693	.01681	.01676	.01675
			Shearing Strength, kg/cm²		
20,000	1,350	1,680	1,630	1,600	1,580
40,000	2,760	3,000	2,930	2,860	2,670
60,000	4,320	4,300	4,010	4,200	3,820
80,000	6,420	5,920	5,310	6,020	5,290

position. The highest concentration, 18.64% Mn, showed a well defined reversible discontinuity of magnitude more than ten times the deviation of any single reading from a smooth curve, and more than three times the hysteresis between ascending and descending readings. This hysteresis was exhibited only at pressures below the transition, and doubtless corresponds to the hysteresis at the lower concentrations over the entire pressure range. It would seem that there is some connection between the transition found here and the possible ordering or phase change remarked by Otter for this composition at temperatures around 300° to 400° at atmospheric pressure.

The general effect of adding manganese to gold is to increase the compressibility.

The shearing strength of the alloys is, at low pressures, greater than that of pure gold, and at the highest pressures not greatly different on the whole, although it is irregular. With increasing concentration of manganese there is a progressive change of shape of the shearing curve, the upward curvature characteristic of pure gold becoming less and eventually vanishing for the highest concentration, for which the curve is sensibly linear over its entire length.

Gold — Palladium. Four compositions were available from Otter, ranging up to 3.99 At % Pd. Hansen and Metals Handbook agree in showing a homogeneous solid solution over the entire composition range.

The results are shown in Table V. Resistance decreases smoothly with pressure, without episode, over the entire range of pressure and composition. The magnitude of the decrease decreases with increasing palladium content.

The compressibility of two of the compositions, 0.81 and 3.99 Pd, showed disturbances at the higher pressures sufficiently definite to justify recording in the table, where a slight reversible *increase* of volume is shown at 25,000. The volume increase was, of course, not directly measured, but was calculated under the usual assumptions from an observed increase of length. Thermodynamically, a reversible increase of volume with increasing pressure is not possible, and the only significance to be ascribed to the entry in the table is a purely formal one, namely that a disturbance was found at this pressure, the exact nature of which is in doubt, but which

certainly cannot be a disturbance corresponding to a uniform increase of volume in all directions. The two intermediate compositions, 1.82 and 3.01 Pd, showed no discontinuity, but were unusual in the larger than usual hysteresis, which furthermore was in the abnormal direction. There is doubtless some connection with the discontinuities shown by the other compositions. It would seem fairly certain that the system is not in a state of complete internal equilibrium, with the presumption that the phase diagram is more complicated than known up to the present.

The shearing results are not particularly regular. On the whole, the shearing strength increases with addition of palladium at the low pressures and decreases at the higher pressures. The regular progression of curvature with composition shown by some of the other gold alloys is not shown here.

Gold – Platinum. Four alloys were available from Otter, ranging up to 4.04 per cent platinum. Hansen and Metals Handbook agree in showing a range of homogeneous solid solution at each end of the composition range, with a very considerable intermediate heterogeneous mixed crystal range, which the Handbook remarks may extend up to 85 or 90 per cent gold at low temperatures. The presumption would seem to be that the compositions studied here are all in the homogeneous range. The internal evidence did not bear out this expectation, however.

The results are shown in Table VI. Measurements were first made on the resistance of the four compositions up to 30,000 kg/cm^2. These specimens were rolled to a thickness of 0.002 inch from the original wire and after rolling quenched from a temperature of 700° C. For any one composition the resistance decreased smoothly with pressure, but the progression of pressure coefficient with composition was highly anomalous, the decrease of resistance for the 3.10 composition being notably larger than for compositions either smaller or larger. The normal sequence would be a continuously decreasing pressure coefficient with increasing concentration. As a check, the measurements were repeated for the first three compositions on new specimens prepared from the original wire by as nearly as possible the identical procedure. The abnormal increase of pressure coefficient at the composition 3.10 was again found, but there were numerical discrepancies between the two sets of runs on ostensibly identical material which were far beyond

any possible experimental error. The values for the fractional decrease of resistance under 30,000 were respectively: for the 1.01 composition, 0.0173 and 0.0217; for the 2.02 composition, 0.0147 and 0.0266; and for the 3.10 composition 0.0268 and 0.0324. The decrement for the first specimen of the composition 4.04 was 0.0146. The identical specimens of the first set of measurements were now subjected to an additional heat treatment by annealing in vacuum at 400° for an hour and cooling with the furnace over night. Runs made on the specimens thus seasoned now gave for the

TABLE VI

Gold – Platinum System

	Au 100	Au 98.99 Pt 1.01	Au 97.98 Pt 2.02	Au 96.90 Pt 3.10	Au 95.96 Pt 4.04
$\rho \times 10^6$	2.19	4.01	4.94	6.20	7.19
Temperature Coefficient	.00391	.00250	.00209	.00165	.00138
Pressure kg/cm²			Rp/Ro		
0	1.0000	1.0000	1.0000	1.0000	1.0000
5,000	0.9849	0.9965	0.9971	0.9949	0.9972
10,000	0.9707	0.9934	0.9944	0.9902	0.9945
15,000	0.9571	0.9905	0.9920	0.9856	0.9920
20,000	0.9441	0.9878	0.9892	0.9812	0.9897
25,000	0.9316	0.9852	0.9872	0.9771	0.9875
30,000	0.9194	0.9827	0.9853	0.9732	0.9854
40,000	0.896	0.978	0.982	0.967	0.982
50,000	0.874	0.974	0.980	0.961	0.979
60,000	0.855	0.971	0.978	0.957	0.976
70,000	0.840	0.968	0.976	0.953	0.974
80,000	0.829	0.965	0.975	0.949	0.972
90,000	0.821	0.963	0.974	0.947	0.971
100,000	0.816	0.961	0.973	0.945	0.970
			$-\Delta V/Vo$		
5,000	.00281	.00296	.00296	.00294	.00293
10,000	.00558	.00586	.00588	.00583	.00581
15,000	.00831	.00873	.00874	.00868	.00863
20,000	.01101	.01156	.01158	.01147	.01143
25,000	.01367	.01434	.01437	.01426	.01419
30,000	.01626	.01708	.01711	.01697	.01691
			Shearing Strength, kg/cm²		
20,000	1,350	1,370	1,530	1,490	1,510
40,000	2,760	2,690	2,780	2,840	2,950
60,000	4,320	4,100	4,010	4,110	4,460
80,000	6,420	5,500	5,310	5,360	6,050

decrements of relative resistance at 30,000: 0.0184, 0.0173, 0.0322 and 0.0181 respectively for the four compositions. Again the results were perfectly smooth in pressure for a single composition. In general the results for the annealed material differ from those for the quenched material by an amount less than the differences between the two sets on ostensibly similar quenched material, except for the anomalous composition 3.10, for which the annealed and the second quenched specimen gave nearly equal values. It is to be noticed that, unlike the pressure coefficients, the values of specific resistance and temperature coefficient of resistance of the 3.10 composition fall in the regular sequence with the other compositions.

It was concluded from these three sets of resistance measurements that the alloys are not in internal equilibrium, and that the attainment of internal equilibrium with reproducible results would be a matter of some difficulty, and would demand a more elaborate investigation than I had time or material to make. The results are accordingly given as they were obtained, for what they may be worth, as an indication of possible behavior. The resistances given in Table VI as a function of pressure are those of the first set on material quenched from 700° C. The resistances above 30,000 in the table were measured on the identical specimens used for resistances below 30,000. The anomalously great decrease of resistance of the 3.10 composition is seen to persist over the pressure range to 100,000.

The compressibility measurements gave no indication of anything unusual at the higher pressures, but all four compositions consistently indicated some sort of internal disturbance at pressures of 5,000 or lower. The disturbances are not of sufficient regularity to characterize either as a phase change or a discontinuity of tangent. In the extreme case this disturbance amounted to a change of length of less than one per cent of the maximum pressure effect. The irregularities are doubtless connected in some way with the irregularities shown by the resistance. It is to be noticed that the compression of the composition 3.10 is not significantly different from that of the others.

The shearing strength shows no notable feature – on the whole the strength of the alloys tends to be greater than that of pure gold at the low pressures and less at the high – a tendency found before.

Copper – Chromium. Hansen and the Metals Handbook agree in a phase diagram in which the range of solubility of chromium in copper is extremely narrow, most of the composition range being occupied by a mechanical mixture. Three compositions from Otter were available for these measurements: 0.061, 0.122, and 0.182 per cent Cr. Otter remarks that the composition 0.061 is probably approaching the solubility limit; the other two compositions therefore probably exceed it.

The results are shown in Table VII. The resistance decreases

TABLE VII

Copper – Chromium System

	Cu 100	Cu 99.939 Cr 0.061	Cu 99.878 Cr 0.122	Cu 99.818 Cr 0.182
$\rho \times 10^6$	1.69	1.70	1.76	1.78
Temperature Coefficient	.00436	.00384	.00378	.00366
Pressure kg/cm²		Rp/Ro		
0	1.00000	1.0000	1.0000	1.0000
5,000	0.99054	0.9925	0.9919	0.9926
10,000	0.98195	0.9853	0.9843	0.9853
15,000	0.9737	0.9782	0.9767	0.9783
20,000	0.9656	0.9715	0.9697	0.9715
25,000	0.9579	0.9649	0.9630	0.9650
30,000	0.9506	0.9587	0.9566	0.9590
40,000	0.939	0.949	0.946	0.948
50,000	0.928	0.940	0.938	0.939
60,000	0.919	0.933	0.929	0.930
70,000	0.911	0.927	0.922	0.923
80,000	0.903	0.922	0.915	0.917
90,000	0.896	0.917	0.909	0.912
100,000	0.890	0.914	0.905	0.907
		$-\Delta V/Vo$		
5,000	.00353	.00356	.00357	.00359
10,000	.00696	.00707	.00710	.00713
15,000	.01039	.01054	.01059	.01062
20,000	.01370	.01396	.01403	.01407
25,000	.01695	.01734	.01743	.01746
30,000	.02010	.02068	.02077	.02084
		Shearing Strength, kg/cm²		
20,000	1,600	1,920	1,910	1,890
40,000	3,420	3,440	3,360	3,350
60,000	5,090	5,020	4,800	4,720
80,000	6,410	6,850	6,730	6,450

smoothly with increasing pressure for all three compositions. Particularly for the 0.061 composition there is no change of direction of the curve which might be associated with a shift of the solubility limit under pressure. It is to be remarked, however, that the progression with composition of the pressure effect is not normal. The decrease of resistance with pressure of the 0.122 composition is slightly greater than for the 0.061 composition instead of less as expected, and the decrease for the 0.182 composition is practically identical with that of the 0.061 composition, instead of materially less. These effects are consistent with 0.061 being very close to the solubility limit.

The compressibilities of all three compositions are very nearly the same and materially less than that of pure copper. The volume is a smooth function of pressure, with no episode.

Comment is required on the compression of pure copper given in the table. I have made determinations of the compression of two different specimens of 99.999 per cent copper, which differ in absolute magnitude by about 5 per cent, far beyond the error of measurement. In the fifth paper of this series the compressions given for pure copper were those most recently determined, which were the high values. The material of that paper offered no definite internal evidence as to which value was preferable, since the compositions of the alloys were not close enough to that of pure copper to give presumptive evidence. With the dilute alloys of this paper, however, the presumption must be that the compression of the alloys should not be far from that of pure copper. It would thus appear that the more recent value for pure copper is distinctly too high, but that on the other hand the earlier value fits well in line. Accordingly in the table the earlier value for 99.999 copper is used.[4] The difference between the two specimens of copper is doubtless an effect of mechanical flaws. It would have been desirable if the compression measurements could have been made on single crystal material, which was not the case for either set of measurements.

The shearing strength shows no notable feature; at low pressure the strength of the alloys is somewhat greater than that of pure copper, but at high pressures roughly the same.

Copper – Manganese. Eleven different compositions were available from Otter, ranging up to 9.14 per cent manganese. Of these,

TABLE VIII

Copper – Manganese System

	Cu 100	Cu 99.943 Mn 0.057	Cu 99.884 Mn 0.116	Cu 99.769 Mn 0.231	Cu 98.85 Mn 1.15	Cu 97.69 Mn 2.31	Cu 95.40 Mn 4.60	Cu 93.12 Mn 6.88	Cu 90.86 Mn 9.14
$\rho \times 10^6$	1.69	1.78	1.91	2.66	4.80	7.92	12.88	17.39	25.10
Temperature Coefficient	.00436	.00367	.00345	.00286	.00119	.00066	.00057	.00051	.000098
Pressure kg/cm²					Rp/Ro				
0	1.00000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
5,000	0.99054	0.9938	0.9949	0.9975	1.0051	1.0083	1.0105	1.0110	1.0118
10,000	0.98195	0.9878	0.9899	0.9951	1.0104	1.0165	1.0209	1.0220	1.0237
15,000	0.9737	0.9820	0.9853	0.9930	1.0157	1.0248	1.0312	1.0330	1.0355
20,000	0.9656	0.9765	0.9808	0.9911	1.0215	1.0330	1.0414	1.0440	1.0473
25,000	0.9579	0.9714	0.9766	0.9893	1.0267	1.0414	1.0516	1.0550	1.0592
30,000	0.9506	0.9666	0.9729	0.9877	1.0323	1.0498	1.1618	1.0659	1.0710
40,000	0.939	0.959	0.966	0.985	1.048	1.066	1.081	1.087	1.094
50,000	0.928	0.953	0.960	0.983	1.063	1.081	1.098	1.109	1.117
60,000	0.919	0.947	0.956	0.980	1.085	1.096	1.116	1.131	1.140
70,000	0.911	0.942	0.951	0.979	1.110	1.114	1.133	1.153	1.163
80,000	0.903	0.938	0.947	0.977	1.137	1.134	1.152	1.174	1.186
90,000	0.896	0.935	0.944	0.976	1.171	1.157	1.172	1.196	1.210
100,000	0.890	0.932	0.942	0.976	1.209	1.181	1.195	1.219	1.235
					$-\Delta V/Vo$				
5,000	.00353	.00357	.00346	.00346	.00351	.00354	.00368	.00373	.00379
10,000	.00696	.00710	.00697	.00694	.00697	.00710	.00732	.00748	.00763
15,000	.01039	.01058	.01051	.01040	.01042	.01062	.01095	.01124	.01151
20,000	.01370	.01401	.01404	.01385 .01438	.01382	.01413	.01452	.01496	.01527
25,000	.01695	.01740	.01750	.01754	.01722 .01759	.01762	.01807	.01851	.01890
30,000	.02010	.02075	.02079	.02068	.02092	.02107	.02157	.02194	.02244
					Shearing Strength, kg/cm²				
20,000	1,600	1,800	1,560	1,790	1,920	2,030	2,220	2,410	2,340
40,000	3,420	3,540	3,370	3,260	3,120	3,500	3,400	3,540	3,900
60,000	5,090	5,480	5,640	4,780	4,450	4,720	4,580	4,750	5,290
80,000	6,410	7,960	8,140	6,700	5,650	6,260	5,990	4,610	6,710

six compositions were in the range below one per cent. It seemed that these six compositions were more closely spaced than necessary for the present work, and accordingly only three of the compositions below one per cent were subjected to pressure, making eight compositions in all for which data are given in Table VIII. Hansen and Metals Handbook agree in a phase diagram which at the copper rich end consists of a range of homogeneous solid solutions presumably extending at room temperature to a composition in the neighborhood of 15 per cent manganese.

For all compositions resistance is a smooth function of pressure, with no episodes. For low concentrations of manganese, resistance decreases under pressure, as it does for pure copper, but for higher concentrations increases. At all concentrations resistance either increases or decreases monotonically with pressure over the entire pressure range. It would have been interesting to study from this point of view a composition for which the initial pressure effect would be expected to be vanishingly small. Interpolation indicates that this would occur at approximately 0.4 Mn. At the higher concentrations the increase of resistance with pressure is approximately linear in pressure, but at the lower concentration there is appreciable deviation from linearity in the normal direction (resistance concave upward).

The compression of two of the compositions, 0.231 and 1.15 per cent Mn, exhibited disturbances from smoothness sufficiently marked to justify reproducing in the table as a discontinuity and phase change. These are small, however, and must be regarded as very doubtful, particularly in view of the very nearly equal irregularity of many of the other points. One would not go far wrong to smooth the results right over the discontinuities given in the table. It is to be noticed that the compressions vary rather consistently over the entire concentration range. At first, the compression diminishes with increasing content of manganese, but in the neighborhood of two per cent there is a reversal, and from here on compression increases with increasing manganese. Such an initial decrease is not uncommon in dilute solutions and is to be explained by something equivalent to an increase of internal pressure with increasing concentration of the solute.

The shearing measurements showed no episode with one notable exception. For the composition 6.88 per cent Mn shearing strength

increases normally up to about 65,000 kg/cm², beyond which there is a cusp-like down turn, with the result that the strength at 80,000 is less than at 60,000. This cusp was reversible with decreasing pressure. The normal interpretation would be that it is a phase transition, perhaps of the rare type that occurs only with the cooperation of shearing stress. It is puzzling, however, that the transition was not found for other concentrations.

Copper – Palladium. Four compositions were available from Otter, ranging from 1.00 up to 4.09 per cent. The phase diagrams of Hansen and of Metals Handbook indicate regions of complicated order-disorder transformations at temperatures beginning at 600° C and extending downward with nebulously widening borders, with the retention of very slow transitions extending over months at room temperature (according to Metals Handbook) for compositions of ill defined limits. It would appear, therefore, that one should be prepared to find evidences of internal instabilities in the measurements made here.

The results are collected in Table IX. The resistance shows no episode of the nature of a discontinuity or a cusp, and the individual points lie smoothly with increasing and decreasing pressure. There is, however, consistent hysteresis, in the normal direction, between the resistances with increasing and decreasing pressure, increasing in magnitude with increasing palladium content. For the composition 4.09 Pd, the maximum width of the hysteresis loop, at the middle of the pressure range, has risen to 7 per cent of the total change of resistance under 15,000. The resistances given in Table IX up to 30,000 are the mean of results with increasing and decreasing pressure, neglecting hysteresis. As normal, the effect of increasing amounts of palladium is to decrease the numerical magnitude of the pressure effect on resistance. This continues over the entire pressure range, up to 100,000.

The compressions given in Table IX indicate a small reversible transition near 20,000 for the two more dilute solutions, 1.00 and 2.01 Pd. These transitions are small but apparently quite definite, the magnitude of the jump at the transition being several fold greater than the irregularity of the individual points above and below the transition. The compressibility of the high pressure phase is definitely less than that of the low pressure phase. This means that no significance should be ascribed to the fact that the table

makes the volume change for the composition 2.01 slightly greater than for the composition 1.00. The amount of the discontinuity depends sensitively on the precise pressure of the transition, in view of the difference of compressibility, and the pressure of the transition could not be located accurately because of the sluggishness of the transition. It is not impossible that the next composition, 3.05% Pd, also has a transition at a somewhat lower pressure. But if so, it is smaller than for the other two compositions and so close in magnitude to the irregularity of the individual readings that no cer-

TABLE IX

Copper – Palladium System

	Cu 100	Cu 99.00 Pd 1.00	Cu 97.99 Pd 2.01	Cu 96.95 Pd 3.05	Cu 95.91 Pd 4.09
$\rho \times 10^6$	1.69	2.46	3.32	3.60	4.86
Temperature Coefficient	.00436	.00269	.00200	.00158	.00134
Pressure kg/cm²			Rp/Ro		
0	1.00000	1.0000	1.0000	1.0000	1.0000
5,000	0.99054	0.9956	0.9972	0.9983	0.9990
10,000	0.98195	0.9910	0.9944	0.9967	0.9980
15,000	0.9737	0.9866	0.9918	0.9951	0.9969
20,000	0.9656	0.9823	0.9893	0.9936	0.9960
25,000	0.9579	0.9784	0.9870	0.9922	0.9953
30,000	0.9506	0.9750	0.9849	0.9909	0.9945
40,000	0.939	0.969	0.981	0.989	0.993
50,000	0.928	0.964	0.978	0.987	0.992
60,000	0.919	0.960	0.975	0.985	0.991
70,000	0.911	0.956	0.973	0.984	0.990
80,000	0.903	0.953	0.972	0.983	0.990
90,000	0.896	0.950	0.970	0.982	0.990
100,000	0.890	0.948	0.969	0.982	0.989
			$-\Delta V/Vo$		
5,000	.00353	.00344	.00348	.00343	.00362
10,000	.00696	.00690	.00691	.00687	.00718
15,000	.01039	.01032	.01034	.01029	.01068
20,000	.01370	.01375 .01398	.01370 .01403	.01368	.01416
25,000	.01695	.01720	.01725	.01709	.01760
30,000	.02010	.02040	.02034	.02064	.02100
			Shearing Strength, kg/cm²		
20,000	1,600	1,750	1,820	1,870	2,380
40,000	3,420	3,500	4,060	3,620	4,150
60,000	5,090	5,260	5,950	5,430	5,580
80,000	6,410	7,490	5,440	7,680	7,450

tainty could be ascribed to it, and the calculations were made on the basis of a smooth curve drawn right through the questionable transition. Readings for the next composition were obtained only with increasing pressure and to a maximum of 25,000. These readings gave no evidence of the expected transition. On trying for the final point at 30,000 the explosion occurred already referred to which destroyed the piezometer. It would have been futile to try to repeat the measurements with the other piezometer, since the

TABLE X

Copper – Platinum System

	Cu 100	Cu 99.672 Pt 0.328	Cu 99.340 Pt 0.660	Cu 99.004 Pt 0.996	Cu 98.662 Pt 1.338
$\rho \times 10^8$	1.69	2.45	3.35	3.81	4.86
Temperature Coefficient	.00436	.00298	.00229	.00189	.00151
Pressure kg/cm²			Rp/Ro		
0	1.00000	1.0000	1.0000	1.0000	1.0000
5,000	0.99054	0.9945	0.9965	0.9973	0.9982
10,000	0.98195	0.9892	0.9930	0.9947	0.9965
15,000	0.9737	0.9841	0.9896	0.9923	0.9949
20,000	0.9656	0.9793	0.9864	0.9900	0.9936
25,000	0.9579	0.9747	0.9832	0.9878	0.9924
30,000	0.9506	0.9703	0.9801	0.9857	0.9913
40,000	0.939	0.963	0.975	0.982	0.989
50,000	0.928	0.956	0.970	0.979	0.988
60,000	0.919	0.951	0.966	0.977	0.987
70,000	0.911	0.946	0.962	0.975	0.986
80,000	0.903	0.942	0.959	0.974	0.985
90,000	0.896	0.938	0.956	0.972	0.984
100,000	0.890	0.936	0.955	0.971	0.984
			$-\Delta V/Vo$		
5,000	.00353	.00337	.00344	.00332	.00335
10,000	.00696	.00672	.00688	.00663	.00667
15,000	.01039	.01001	.01026	.00987	.00995
20,000	.01370	.01324	.01357	.01306	.01315
25,000	.01695	.01722 (a)	.01689	.01624	.01636 .01668
30,000	.02010	.02037	.02014	.01938	.01978
			Shearing Strength, kg/cm²		
20,000	1,600	2,030	1,820	1,890	2,010
40,000	3,420	3,700	3,330	3,680	3,890
60,000	5,090	5,240	4,940	5,100	5,690
80,000	6,410	6,100	5,750	6,710	7,950

(a) Transition at 22,000; $-\Delta/Vo$ .01454 and .01527

performance of this was not good enough to show such small effects with certainty, and there was, in any event, no guarantee that these small phase changes would repeat. Much more elaborate study would be necessary to establish a consistent pattern of behavior here.

In general, the shearing strength of the alloys is greater than that of pure copper, with a tendency to accelerated increase at the higher pressures. The composition 2.01 Pd affords an exception above 60,000. Here the same sort of a drop-back was encountered as already met once before for 93.12 Cu – 6.88 Mn. The interpretation is obscure. The effect will be encountered again in the copper-platinum system and a fuller discussion will be attempted then.

Copper – Platinum. Four compositions were available from Otter, ranging from 0.328 to 1.338 per cent platinum. Both Hansen and Metals Handbook show homogeneous solid solution over the entire composition range above 800° C, and below 800° two regions of complicated internal change, with very nebulous boundaries, which have not been investigated below 400°, but which, according to the curve in Metals Handbook, might possibly extend practically to pure copper at room temperature. It would seem, therefore, that one must be prepared for internal changes in this system.

The results are shown in Table X. The resistances of the three lower concentrations up to 30,000 showed no unusual feature, except a consistent hysteresis, increasing with concentration. The width of the hysteresis loop reached a maximum of 2.5 per cent of the pressure effect of 30,000 for the 0.996 concentration. This hysteresis is thus materially less than for the system copper-palladium. The values in the table are the means with increasing and decreasing pressure. The behavior of the highest concentration, 1.338 per cent Pt, was notably different from that of the others. The points for increasing and decreasing pressure lie smoothly, but with decreasing pressure there is a continually increasing divergence from the points with increasing pressure, until on reaching atmospheric pressure again there is a permanent decrease of resistance of nearly 20 per cent of the maximum pressure effect at 30,000, or 0.2 per cent of the total absolute resistance. The table shows only the points with decreasing pressure. The pressure coefficients follow the usual rule that the numerical magnitude of the decrease

of resistance produced by pressure decreases with increasing concentration of the solute. This holds over the whole pressure range, up to 100,000, and would continue to hold for the 1.338 composition even if the measurements with increasing pressure had been used instead of those with decreasing.

The compressions, as given in the table, indicate reversible transitions for the two compositions 0.328 and 1.338% Pt. The first of these would appear to be beyond reasonable experimental uncertainty, but the latter is smaller, with only two points instead of four to confirm it, and accordingly must be recognized to be in much doubt. The compressibility of the high pressure phase of the lower concentration is very approximately the same as that of the low pressure phase. No statement whatever can be made about the probable relative compressibilities of the two possible phases of the 1.338 concentration.

The shearing strength of the two compositions 0.328 and 0.660 per cent Pt exhibited the same anomaly at the high pressures as have been found for two other copper alloys, one with manganese and one with palladium. The anomaly consists in an abrupt drop in the shearing strength from that to be expected from an extrapolation of the curve for lower pressures. This drop occurred at the two highest pressures of the two former runs, but here, with the platinum alloys, at only the one very highest pressure. In the table the results are given only for large pressure steps. It results because of this that whereas formerly the tabulated results showed an actual drop of strength from 60,000 to 80,000, here the strength at 80,000 is greater than at 60,000, but the difference is much less than would have been extrapolated from the lower pressures. If the present results had been tabulated at smaller pressure intervals, an actual maximum would have been shown at about 75,000 – the maximum for the other two alloys would have been nearer 65,000.

The interpretation of this drop in the shearing curve is obscure. The general behavior is quite unlike that found before when we are concerned with a conventional transition, like that of bismuth, for example. For such a transition, the behavior of the rotating handle of the shearing apparatus above and below the transition pressure is quite conventional. Above and below the rotation is smooth, at constant torque, but with merely the feature that the torque required to produce rotation is less at the higher pressure instead of

greater. But here there is some sort of instability. At first the torque on the rotating handle is as high as would be anticipated from the readings at lower pressures, but presently, during the rotation, the torque suddenly drops to a lower value, which mostly persists during the rest of the rotation, but which sometimes will rise again to the high value, only to drop again. The shearing strengths tabulated are the low values, the high values showing no consistency. One is reminded of the difference between static and sliding friction. It is perhaps possible that there is some drastic modification in the mechanism of surface slip at the high pressure, but there has been no previous indication of it, and the coefficient of friction is normally so high that the surfaces should remain comfortably frozen together once the critical pressure (which is very low) has been exceeded. There was no indication of any permanent damage to the carboloy surface after the occurrence of this sort of thing, as might be expected if surface slip is responsible. The rotation is too slow to make elevation of temperature a reasonable explanation, and it is to be remembered that this effect has been found only with alloys of copper, with presumably a higher than normal thermal conductivity. Some kind of a transition which occurs only in the presence of a shearing force greater than a critical value appears to me the most probable explanation.

Four Alloys of Silver. Four alloys of silver, one each with cadmium, indium, magnesium, and zinc, were obtained from Professor Smith and Mr. Bacon of Case Institute. As already mentioned, the chief interest was to compare the compressibility with that calculated from the conventional elastic constants as measured at Case Institute. The complete phase diagrams of these four alloys is unusually complicated, but all have a range of homogeneous solid solution at the silver rich end which should extend comfortably beyond the range of composition of the present alloys.

The results are shown in Table XI. Up to 30,000 the resistances of the alloys of cadmium, indium, and zinc show no noteworthy feature, the points lying smoothly, with no significant hysteresis, except possibly for the zinc alloy which exhibited a hysteresis loop of maximum width, 3 per cent of the maximum pressure effect. The magnesium alloy, on the other hand, was the seat of some internal change. With increasing pressure, up to 15,000, resistance decreased with abnormal increasing downward curvature, which

reversed at higher pressures. On release of pressure, curvature was normal throughout, with the result that on return to atmospheric pressure there was a permanent decrease of resistance of 0.71 per cent of the total absolute value, or 25 per cent of the pressure effect. Points with increasing and decreasing pressure lay smoothly. The table shows only the points with decreasing pressure. None of the alloys exhibited any further anomaly in the range from 30,000 to 100,000. It must be remembered, however, that the method used

TABLE XI

Four Alloys of Silver

	Ag 100	Ag 98.70 Cd 1.30	Ag 91.40 In 8.60	Ag 96.92 Mg 3.08	Ag 96.44 Zn 3.56
$\rho \times 10^6$	1.67	1.74	11.55	4.88	2.26
Temperature Coefficient	.00381	.00377	.00070	.00157	.00311
Pressure kg/cm²			Rp/Ro		
0	1.0000	1.0000	1.0000	1.0000	1.0000
5,000	0.9835	0.9843	0.9931	0.9940	0.9873
10,000	0.9677	0.9698	0.9865	0.9889	0.9752
15,000	0.9592	0.9561	0.9806	0.9839	0.9637
20,000	0.9392	0.9430	0.9748	0.9795	0.9528
25,000	0.9263	0.9307	0.9693	0.9752	0.9424
30,000	0.9141	0.9188	0.9640	0.9714	0.9326
40,000	0.889	0.898	0.956	0.965	0.916
50,000	0.868	0.882	0.950	0.960	0.903
60,000	0.850	0.867	0.945	0.956	0.891
70,000	0.835	0.854	0.940	0.952	0.880
80,000	0.823	0.843	0.936	0.949	0.871
90,000	0.813	0.832	0.933	0.947	0.863
100,000	0.806	0.823	0.930	0.945	0.857
			$-\Delta V/Vo$		
5,000	.00473	.00448	.00489	.00418	.00486
10,000	.00938	.00894	.00965	.00839 .00971	.00956
15,000	.01385	.01336	.01420	.01385	.01395
20,000	.01820	.01770	.01850	.01792	.01807
25,000	.02236	.02204	.02275	.02201 .02321	.02205 .02349
30,000	.02619	.02635	.02683	.02683	.02728
			Shearing Strength, kg/cm²		
20,000	1,120	1,960	1,890	1,220	2,080
40,000	2,050	2,900	3,030	2,280	3,300
60,000	2,810	3,590	3,520	3,280	3,970
80,000	3,750	4,140	4,250	4,020	4,540

for the measurements to 100,000 does not permit readings with decreasing pressure, so that we cannot tell whether further additional permanent alterations in resistance were produced in the magnesium alloy at pressures above 30,000. All these alloys show the expected behavior of a smaller pressure decrease of resistance than for pure silver.

The compressions of the cadmium and indium alloys show no noteworthy feature. The compressibility of the indium alloy starts somewhat higher than that of pure silver and runs consistently higher over the entire pressure range. The compression of the cadmium alloy, on the other hand, is initially appreciably lower than that of pure silver, but with increasing pressure the gap closes until at 30,000 the alloy is slightly higher. The magnesium alloy shows two small reversible transitions, which are almost certainly beyond experimental error. The behavior of the resistance of this alloy perhaps prepares one for something of the sort. The compressibilities of the three modifications are very approximately the same. The table indicates an initial compressibility for the low pressure modification markedly less than that of pure silver, and for that reason is somewhat implausible. The experimental uncertainty here must be recognized to be somewhat greater than usual, since the pressure range on which this value depends is only 5,000 kg/cm^2. It seems to me, however, that considerable violence would have to be done to the experimental points to make them yield a compressibility as high as pure silver. The mean over-all compression up to 30,000, including the transitions, is in line with that of the other alloys. Finally, the zinc alloy has a small reversible transition, running with increasing pressure somewhere between 25,000 and 30,000 and reversing with decreasing pressure somewhere between 27,500 and 22,500. Since there are only two points for the high pressure modification, neither the change of volume nor the compressibility of the high pressure phase can claim any great accuracy.

The initial compressibilities at atmospheric pressure may be obtained by linear extrapolation of the volume decrements given in the table for 5,000 and 10,000 kg/cm^2. The values so obtained for the alloys of cadmium, indium, magnesium, and zinc, times 10^{-7}, are respectively: 8.98, 9.91, 8.33, and 9.88, the pressure unit being the kg/cm^2. The values of Bacon[5], expressed in the same units, are respectively: 10.07, 9.63, 9.79, and 10.13. The agreement is not

good, and there is no consistency in the direction of disagreement. I believe, however, that the probability is that my value for the magnesium alloy is too low, the determination of compressibility having been complicated by the occurrence of the transition.

The shearing strengths of the alloys of cadmium, indium, and zinc are, at the low pressures, markedly greater than that of pure silver, but increase with pressure less rapidly, until at 80,000 they only somewhat surpass pure silver. The shearing curve of the indium alloy is notable for an unusually pronounced reversal of curvature at the upper end, and for the fact that the curve with decreasing pressure is indistinguishable from that with increasing pressure. The shearing curve for the magnesium alloy starts much lower than the others, being almost as low as pure silver, but rises approximately linearly at a rate somewhat higher than that of the other alloys, until at 80,000 it is not markedly out of line. The initial low value for this alloy may be connected with the low pressure transition shown by the compression.

Iron — Nickel. Five alloys were available for which I am indebted to Professor Morris Cohen of the Department of Metallurgy of M. I. T. and to Mr. L. Kaufman, who did the actual work of preparation. These alloys were subjected to an elaborate process of preparation which is described in detail in Mr. Kaufman's letter, which I quote. I have converted his weight percentages to atomic percentages.

"The compositions were respectively: 14.42, 19.10, 23.84, 33.1 and 37.0 atomic per cent nickel. Of these the first three are body centered cubic and the last two face centered cubic.

Starting with the as-cast condition the following treatment was carried out in order to convert the ingots into 1/16 inch rods suitable for resistance measurements.

1. 50 hours anneal at 2000° F (water quench to room temperature).
2. Swage to 0.120 inch diameter rod.
3. One hour anneal at 2000° F (water quench).
4. Swage to 0.090 inch.
5. One hour anneal at 2000° F (water quench).
6. Swage to 0.062 inch (1/16 inch).
7. 24 hour anneal at 2000° F (water quench).
8. One hour anneal at 2000° F (water quench).

Annealing treatments were carried out in evacuated vycor capsules.

The purpose of the final one hour anneal was to remove slight cold work incurred in separating the rods, which were lightly welded together during the previous 24 hour anneal.

This treatment should yield uniform material with an average grain diameter of 0.1 mm.

These alloys undergo an allotropic f.c.c. → b.c.c. transformation on cooling and b.c.c. → f.c.c. transformation on heating. The M_s (f.c.c. → b.c.c.) and A_s (b.c.c. → f.c.c.) temperatures for each alloy, as determined by resistance measurements, are as follows:

At % Ni	M_s	A_s
14.42	525° C	685° C
19.10	350	625
23.84	200	570

The 33.1 and 37.0% alloys will not undergo f.c.c. → b.c.c. transformations even when cooled to 4° K (liquid helium).

The resistivity of the f.c.c. structure is about 90×10^{-6} ohm-cm at 25° C, while the resistivity of the b.c.c. structure is about 40×10^{-6} ohm-cm at room temperature.

The f.c.c. → b.c.c. reaction can be induced in the 33.1% alloy by cooling a specimen in liquid nitrogen and bending it."

The material as furnished me was in the form of wire approximately 1/16 inch in diameter. Measurements on the wire, as received, were made of specific resistance and temperature coefficient of resistance at atmospheric pressure and of compression up to 30,000 kg/cm². For the resistance measurements under pressure short lengths of the wires were cold rolled to a thickness of approximately 0.002 inch (all the compositions were soft and the rolling was easy), and then subjected to an additional annealing treatment by me to remove any mechanical strains left by the rolling. For the three alloys with lower nickel content, which normally occur in the b.c.c. lattice, the annealing temperature was taken as 450° for the most dilute and 400° C for the other two so as to avoid any danger, according to Mr. Kaufman's table, of inducing the b.c.c. to f.c.c. transition by annealing. The two higher compositions, being normally in the f.c.c. arrangement, presented no such danger of a transition and the annealing temperatures for them were accordingly taken as a red heat.

One alloy, composition 19.1% Ni, was studied in both the un-

annealed and annealed condition after rolling. The temperature coefficients were respectively 0.00230 and 0.00226 and the specific resistances at 0° 31.7 and 30.6 $\times$ 10^{-6}. The latter certainly agree within experimental error, and the difference between the temperature coefficients is probably not significant either, so that the conclusion was drawn that the annealing after rolling was hardly necessary. Later measurements of specific resistance and temperature coefficient of the same composition in the form of wire "as received" gave 28.8 for specific resistance and 0.00240 for temperature coefficient. The specific resistance cannot be positively said to be

TABLE XII

Five Iron – Nickel Alloys

	Fe 85.58 Ni 14.42	Fe 80.90 Ni 19.10	Fe 76.16 Ni 23.84	Fe 66.9 Ni 33.1	Fe 63.0 Ni 37.0
$\rho \times 10^6$	28.6	28.8	28.1	79.4	63.1
Temperature Coefficient	.00217	.00240	.00272	.00130	.00281
Pressure kg/cm²			Rp/Ro		
0	1.0000	1.0000	1.0000	1.0000	1.0000
5,000	1.0029	1.0081	1.0128	1.0116	1.0483
10,000	1.0054	1.0152	1.0240	1.0161	1.0899
15,000	1.0075	1.0217	1.0356	1.0158	1.1259
20,000	1.0092	1.0277	1.0463	1.0117	1.1563
25,000	1.0105	1.0335	1.0566	1.0055	1.1804
30,000	1.0116	1.0390	1.0666	0.9976	1.1978
40,000	1.012	1.047	1.084	0.982	1.221
50,000	1.012	1.053	1.098	0.967	1.231
60,000	1.011	1.058	1.110	0.954	1.235
70,000	1.011	1.062	1.121	0.942	1.236
80,000	1.012	1.066	1.133	0.931	1.237
90,000	1.014	1.069	1.146	0.922	1.237
100,000	1.015	1.073	1.158	0.916	1.240
			$-\Delta V/Vo$		
5,000	.00332 (a)	.00296	.00300	.00434 .00562	.00385
10,000	.00634	.00591	.00602	.00956	.00771
15,000	.00924	.00879	.00899	.01360	.01176 (b)
20,000	.01207	.01161	.01190	.01756	.01577
25,000	.01488	.01445	.01477	.02154	.01983
30,000	.01767	.01720	.01751	.02544	.02381

(a) Cusp at 6,000; $-\Delta V/Vo$ .00401

(b) Cusp at 11,200; $-\Delta V/Vo$ .00862

significantly different from that of the rolled material, because of the unfavorable geometrical dimensions of the rolled material, but the difference of temperature coefficients is certainly beyond the error of the individual measurements and probably significant.

In spite of the fact that measurements of specific resistance and temperature coefficient had indicated that annealing after rolling produces little effect, measurements were made on the effect of pressure on the resistance of both annealed and unannealed material of the composition 19.1% Ni. It was a surprise to find a very material difference in the behavior of resistance under pressure, the annealed material showing an increase of relative resistance at 30,000 of 0.0390 and the unannealed an increase of 0.0504. This difference persists over the entire pressure range up to 100,000, the relative resistance at 100,000 of the annealed being 1.0729 and of the unannealed 1.1145. Previous experience had hardly prepared me to find the pressure coefficient of resistance more sensitive to internal condition than specific resistance or temperature coefficient.

The resistances given in Table XII are all for the material annealed after rolling. In all cases resistance is smooth in the pressure, with no discontinuities or cusps, and with no appreciable hysteresis, except for the single composition 14.42% Ni, for which there is a slight hysteresis associated with a permanent decrease of resistance after release of pressure of approximately 0.05 per cent. At the lower pressures the resistance of all compositions increases with increasing pressure. Composition 33.1% passes through a well defined maximum, followed by an eventual decrease to approximately 9% less than the initial resistance. The curve for the composition 14.42% rises to a flat maximum, followed by a still flatter minimum with eventual rise again, the total variation of resistance over the entire pressure range being 1.5 per cent. The resistance of the three other compositions rises over the entire pressure range by amounts varying from 7 to 24 per cent, in all cases with downward curvature, which is not the normal curvature for a material with positive pressure coefficient.

The volume change, unlike the resistance, does show episodes, there being two cusps and one volume discontinuity. There is no detectible regularity in the progression of these episodes through the sequence of compositions. This is not surprising in view of the

behavior of pure nickel, which may on occasion show a very pronounced cusp, the details of the appearance of which vary capriciously with the details of the past history of the particular specimen, and which I have never been able to reduce to reliable reproducibility.

The table shows results for only five compositions, but Mr. Kaufman's original letter gives data for six compositions that were furnished me. The sixth composition, not quoted above, was stated to be 9.61% Ni. It would appear, however, that there must have been some slip-up with regard to this alloy, because most of its properties, both at atmospheric pressure and under higher pressure, were indistinguishable from those of 33.1 Ni content, which has a f.c.c. instead of a b.c.c. structure, and a specific resistance nearly three times that of the other. Furthermore, my own previous measurements[6] of the iron-nickel series agreed roughly with the expectation of properties suggested by Mr. Kaufman. I had no alternative, therefore, except to suppose that there had been some mix-up, and that two specimens of 33.1 Ni content had been sent me. The only respect in which the measurements under pressure of the ostensible 9.61 composition were distinguishable from those for composition 33.1 was in the compression. The former showed an obtuse cusp at 18,000 with volume decrement of 0.1633, whereas the latter showed a small volume discontinuity at 5,000, and no cusp at higher pressure. This failure of exact agreement has no significance, because it has been found before that these slight irregularities are capricious and not reproducible. In any event, the volume measurements agreed rather closely: the relative volume decrements at 15,000 of the two compositions were respectively, 0.1366 and 0.1360. The corresponding figures at 30,000 were 0.02510 and 0.02544.

These alloys were too strong to permit measurements of shearing strength.

I have previously[6] measured the effect of pressure on the resistance of a number of iron-nickel alloys, varying from 10 to 70 per cent Ni, and the compressibility to 12,000 of a single composition, "invar", of 37.5 Ni content. The former material had not been subjected to as elaborate heat treatment as that measured here, and the compositions do not exactly correspond. Exact comparison of the results is therefore difficult, particularly in view of the fact

that there are ranges of composition where slight changes make very large changes in behavior, as shown, for example, by the relative behavior of the compositions 33.1 and 37.0 in Table XII. However, when all these factors are discounted, I remain with the impression that the agreement between the present and the former measurements is not as good as it should be. This only emphasizes the fact that the behavior of the iron-nickel series is sensitive to obscure disturbances, and that consistent results are difficult to get. In the large, it would seem that there is a rather definite difference of properties between the f.c.c. and b.c.c. arrangements, but a characterization in terms of the lattice can be only a very rough characterization and other factors must be taken into account.

TABLE XIII

Two Heat Treatments of a 4.31 (At %) Carbon Steel

	Fe 100	Fe 95.69 — C 4.31	
$\rho \times 10^6$	11.3	13.2	
		(1)	(5)
Temperature Coefficient	.00585	.00475	
		.00395	.00448
Pressure kg/cm²		Rp/Ro	
0	1.0000	1.0000	1.0000
5,000	0.9884	0.9904	0.9906
10,000	0.9773	0.9812	0.9814
15,000	0.9666	0.9734	0.9725
20,000	0.9562	0.9639	0.9640
25,000	0.9464	0.9557	0.9556
30,000	0.9368	0.9480	0.9477
40,000	0.920	0.936	0.936
50,000	0.906	0.926	0.925
60,000	0.893	0.918	0.915
70,000	0.881	0.911	0.906
80,000	0.870	0.904	0.897
90,000	0.861	0.898	0.891
100,000	0.852	0.894	0.885
		$-\Delta V/Vo$	
5,000	.00289	.00288	
10,000	.00575	.00578	
15,000	.00856	.00857	
20,000	.01133	.01132	
25,000	.01406	.01407	
30,000	.01676	.01676	

Carbon Steel. Professor Cohen furnished me, through Mr. Lement, with a highly pure carbon steel to be investigated in different heat treatments. The analysis as furnished showed only 0.96 Wt % C (4.31 At %) with no detected Mn, Si or Ni. The material was furnished in the annealed condition, in the form of wire 0.064 inch in diameter. In this condition measurements were made of specific resistance and temperature coefficient of resistance at atmospheric pressure and compression to 30,000. Specimens for the resistance measurements under pressure were rolled from the wire to a thickness of 0.002 inch, and returned to Mr. Lement for further heat treatment. This treatment consisted in the first place of a hardening treatment which consisted of maintaining at 845° C for ½ hour, quenching in iced brine, cooling to -195° C for 1 hour, and returning to room temperature. The specimens were then divided into five groups, and subjected to the following further tempering treatments: 1, none; 2, 93° C for 1 hour; 3, 204° C for 1 hour; 4, 316° C for I hour; 5, 427° C for 1 hour. Of these, the specimens with the tempering treatments 1 and 5 were measured to 30,000 and 100,000 in the regular way. The resistances of these two extreme treatments were so closely the same under pressure that it did not seem worth while to measure the intermediate treatments.

The results are given in Table XIII. In this table the value for the specific resistance, one value of temperature coefficient (0.00475), and the compression are for the annealed material "as received". Values are also given for pure iron for comparison. The two heat treatments exhibit practically the same effect of pressure on resistance, but there is a definite difference in temperature coefficient, that of treatment 5 approaching closer that of the fully annealed material. The effect of added carbon on the pressure coefficient of resistance, namely a diminution in the decrease of resistance, is in the same direction as we have come to expect from other alloys with added metallic elements. The compression of the annealed material is indistinguishable from that of pure iron. I had previously found that the compression of pure martensite differs very little from that of pure iron.[7]

Three Invars. Professor Cohen suggested that it would be of interest to find the effect of varying carbon on the iron-nickel alloy known as invar, and the results are therefore included here, although these are not binary alloys. Three invars were supplied in

the annealed condition with the following compositions (Wt per cents).

No	C	Mn	Si	Ni
N1	0.02	0.09	0.01	36.0
N5	0.25	0.05	0.20	36.6
N7	0.58	0.07	0.22	36.2

The specific resistance, temperature coefficient of resistance and compression were measured on the "as received" material in the form of wire 0.063 inch in diameter. Pieces were cut from these wires, rolled to a thickness of 0.002 inch for the resistance measurements, and returned to Mr. Lement for further heat treatment. This consisted in the first place of heating to 1200° C for 1 hour, quenching in water, reheating to 200° C for 1 hour and quenching in water. Three specimens of the three compositions, designated as N1 – 1, N5 – 1, and N7 – 1, were measured for resistance under pressure without further treatment. Three other specimens, designated as N1 – 2, N5 – 2, and N7 – 2, were subjected to a further aging at 70° C for 500 hours, and then the resistance measured under pressure.

The results are given in Table XIV. The differences between the different carbon contents and different heat treatments are small and not wholly consistent. In general, the properties do not vary monotonically with composition; both the pressure effect on resistance and the compression of the median carbon content are less than that on either side. Furthermore, the intermediate composition shows two volume discontinuities. These are small, however, and particularly the one at 5,000 must be regarded as somewhat in doubt.

Compared with the binary iron-nickel alloys of Table XII the specific resistances, temperature coefficients, and pressure effect on resistance of these invars are all intermediate between the two compositions of greatest nickel content in Table XII. The compressions, however, are on the whole somewhat greater than for the binary alloys.

Discussion and Summary

The material of this paper exhibits no spectacular features in the way of interruptions of smoothness or continuity. The generalization previously found to hold almost without exception with regard

to pressure coefficient of resistance, namely that the addition of a small amount of an alloying element increases algebraically the pressure coefficient of resistance, continues to hold without further exception. There does not, however, seem to be any obvious connection between the numerical magnitude of the alteration of the pressure coefficient and the atomic fraction of added metal.

Manganese, when added in sufficient quantity to copper, silver or gold, changes the sign of the pressure coefficient from negative to positive. The effect deviates markedly from linearity with the composition. Interpolation indicates that the sign of the pressure

TABLE XIV

Three "Invars" With Different Carbon Contents

	N 1		N 5		N 7	
	1	2	1	2	1	2
$\rho \times 10^6$	71.9		71.7		73.8	
Temperature Coefficient	.00213		.00212		.00203	
	.00220	.00226	.00204	.00205	.00220	.00227
Pressure kg/cm²			Rp/Ro			
0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
5,000	1.0362	1.0352	1.0326	1.0326	1.0323	1.0331
10,000	1.0643	1.0698	1.0576	1.0579	1.0609	1.0624
15,000	1.0854	1.0884	1.0761	1.0761	1.0854	1.0886
20,000	1.1000	1.1059	1.0882	1.0882	1.1053	1.1094
25,000	1.1088	1.1179	1.0945	1.0948(a)	1.1200	1.1261
30,000	1.1125	1.1244	1.0965	1.0955	1.1297	1.1365
40,000	1.113	1.126	1.091	1.090	1.140	1.148
50,000	1.105	1.113	1.081	1.081	1.144	1.151
60,000	1.095	1.103	1.071	1.071	1.138	1.146
70,000	1.083	1.093	1.060	1.060	1.136	1.139
80,000	1.070	1.083	1.050	1.049	1.129	1.132
90,000	1.057	1.075	1.040	1.041	1.122	1.125
100,000	1.045	1.068	1.034	1.033	1.117	1.120
			$-\Delta V/Vo$			
5,000	.00482		.00394 .00508		.00478	
10,000	.00948		.00798		.00942	
15,000	.01388		.01278 .01375		.01385	
20,000	.01811		.01759		.01805	
25,000	.02221		.02144		.02214	
30,000	.02616		.02473		.02605	

(a) Maximum, 1.0960 at 28,500

coefficient reverses for the addition of about 0.5 At per cent Mn to copper, 1.5 per cent to silver and 2.5 per cent to gold. Pure manganese decreases in resistance under pressure, with a comparatively large coefficient. A theoretical discussion of the reason for the abnormal effect in alloys would be of interest.

The compressions of the dilute alloys in general differ little from the pure metals. In the majority of cases the dilute alloy is more compressible than the pure metal, even in some cases where the dissolved metal (platinum or palladium) is intrinsically less compressible than the solvent metal.

Small scale irregularities abound. As in earlier papers of this series most of these irregularities are exhibited by the compressions rather than by the resistances, which might perhaps have been thought to be more sensitive. The gold-platinum series shows an abnormal sequence of pressure coefficients of resistance with composition. The copper-palladium and copper-platinum series give evidence of incomplete equilibrium in the resistance phenomena, as shown by hysteresis and a permanent change of resistance after exposure to pressure of the most concentrated Cu-Pt alloy.

The volume abnormalities may be summarized as follows. The gold-manganese series shows a small phase change at the highest concentration and hysteresis at lower concentrations. Gold-palladium shows a reversible *increase* of length for two compositions near 25,000, which thermodynamically cannot mean a volume increase, but must be due to some other obscure instability. Gold-platinum shows irregular compressions at pressures below 5,000 kg/cm^2. Copper-manganese shows various irregularities, rising to the magnitude of definite volume discontinuities for two compositions. Copper-palladium shows small transitions at two composisions. Silver-magnesium and silver-zinc show definite volume discontinuities. The iron-nickel series shows several examples of cusps or volume discontinuities, which vary capriciously with composition, as might be expected from the capricious behavior of pure nickel. Similarly, one of the three "invars" shows two rather large volume discontinuities which do not appear in the two others.

In general, the shearing curves show little episode; the more common tendency is for the shearing strength to increase with addition of alloying metal. An exception is afforded by certain compositions of copper-manganese, copper-palladium, and cop-

per-platinum at the highest pressures. These show a new type of shearing anomaly which consists of a catastrophic drop, during the shearing process, of the shearing strength from a poorly defined upper value to a well defined lower value. The possibility is to be considered of a transition to a modification stable only under shearing stress, or possibly some new two-dimensional surface structure.

As in all this work I am indebted to Mr. Charles Chase for preparing the specimens and setting up the apparatus. Also, as in the previous paper of this series, I am much indebted for grants from the American Philosophical Society and from the Research Corporation with which out-of-pocket expenses to the University have been defrayed.

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